U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-290 472

Impact of Forestry Burning upon Air Quality. A State-of-the-Knowledge Characterization in Washington and Oregon

Geomet, Inc., Gaithersburg, MD

Prepared for

Environmental Protection Agency, Seattle, WA. Region X

Oct 78

EPA 910/9-78-052

United States
Environmental Protection
Agency

Region 10
1200 Sixth Avenue
Seattle WA 98101

PB 290472

October 1978

EPA

Impact of Forestry Burning Upon Air Quality

A State-of-the-Knowledge Characterization in Washington and Oregon

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA 910/9-78-052

2.

3. RECIPIENT'S ACCESSION NO. PB290472

4. TITLE AND SUBTITLE
IMPACT OF FORESTRY BURNING UPON AIR QUALITY
A State-of-the-Knowledge Characterization in Washington and Oregon

5. REPORT DATE October 1978

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S) Jonathan D. Cook, James H. Himel, and Rudolph H. Moyer

8. PERFORMING ORGANIZATION REPORT NO. GEOMET Report Number EF-664

9. PERFORMING ORGANIZATION NAME AND ADDRESS
GEOMET, Incorporated
15 Firstfield Road
Gaithersburg, MD 20760

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO. Contract Number 68-01-4144

12. SPONSORING AGENCY NAME AND ADDRESS
U.S. Environmental Protection Agency
Region X
1200 Sixth Avenue
Seattle, Washington 98101

13. TYPE OF REPORT AND PERIOD COVERED Final--8/15/77-8/15/78

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This document presents a state-of-the-knowledge characterization of the air quality impact of prescribed forestry burning in the Pacific Northwest.

Prescribed forestry burning has been shown to be a useful management tool in the Pacific Northwest. Techniques for burning are well developed. Much is known about fire behavior under controlled burning conditions; less is known about emissions.

Emissions from prescribed forestry burning in this region cannot be accurately estimated from data presently available. The emission factors reported in the literature vary widely, therefore, this report presents ranges of estimated emissions which may reflect the magnitude of forestry burning emissions.

The impact of these emissions cannot be accurately assessed using available dispersion models or air quality monitoring networks. Potential impacts of concern include human health and visibility impairment. The total particulate, hydrocarbon and carbon monoxide emissions from forestry burning are significant and may contribute to exceedance of air quality standards in Washington and Oregon. Some research has been directed toward evaluation of the impact of forestry burning on ambient air quality, particularly in the Willamette Valley, but a consensus of findings does not exist at this time. However, some individual studies have indicated a clear impact.

The impact of prescribed burning can be reduced. Smoke management programs are largely successful in preventing observable smoke intrusions into populated areas; however, the potential for air quality degradation from residual smoke still exists. Alternative burning techniques and alternatives to burning are available. Alternative burning techniques include the use of optimal burn periods, optimal standard techniques and new burning technology. The alternatives to forestry burning include the use of mechanical or chemical treatments, improved harvesting systems, slash utilization and no treatment. (over)

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS

Air Quality Impact
Forestry Burning
Slash Burning
Prescribed Burning
Open Burning
Emissions
Alternatives
Wood Residues
Smoke Management
Utilization

b. IDENTIFIERS/OPEN ENDED TERMS

c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Release to the Public

19. SECURITY CLASS (This Report) UNCLASSIFIED

20. SECURITY CLASS (This page) UNCLASSIFIED

21. NO. OF PAGES 270

22. PRICE A12 - A01

16. ABSTRACT (Continued)

Future legislation and the implementation of legislative mandates of the Clean Air Act Amendments of 1977 may have significant implications. Visibility standards in EPA Class I areas and fine particle legislation by EPA and Congress could impose stricter regulations on forestry burning in the Pacific Northwest.

This report was submitted in fulfillment of Task Order 4 of Contract Number 68-01-4144 by GEOMET, Incorporated under the sponsorship of the U.S. Environmental Protection Agency.

EPA 910/9-78-052

October 1978

IMPACT OF FORESTRY BURNING UPON AIR QUALITY

A State-of-the-Knowledge Characterization in Washington and Oregon

FINAL REPORT

by

GEOMET, Incorporated
Gaithersburg, Maryland 20760

EPA Contract Number 68-01-4144

David C. Bray
Project Officer

U.S. ENVIRONMENTAL PROTECTION AGENCY
REGION X
1200 SIXTH AVENUE
SEATTLE, WASHINGTON 98101

DISCLAIMER

This report has been reviewed by Region X, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

EXECUTIVE SUMMARY

This study characterizes prescribed forestry burning in the states of Washington and Oregon with an emphasis on the region west of the Cascade Mountains. A comprehensive program of literature searches and field interviews was used to develop a state-of-the-knowledge document on forestry burning emissions and their impact on air quality. Methods for reducing the impact of forestry burning on air quality are explored and organizational and research strategies are introduced to improve air quality impact assessment and control.

Prescribed burning is used to reduce or eliminate unwanted natural and man-caused accumulations of slash, brush, litter or duff in a controlled application so as to maximize net benefits with minimum damage and at an acceptable cost. Prescribed burning accomplishes three basic objectives singularly or in combination: reduction of the hazard of wildfire, aid to silvicultural activities and improvement of forage plants and wildlife habitats. The appropriate use or nonuse of prescribed burning depends on an assessment of site-specific variables including fuel, topography, weather, climate, accessibility, manpower, management and environmental considerations. The burning technique and ignition device employed on a given site will depend on these same variables. Prescribed burning is accomplished by broadcast, pile or understory burning and may use such ignition devices as matches, drip torches, napalm or helicopter drip torches.

In the 3-year period from 1975 through 1977, an average of 138,000 acres were burned annually on the west side of the Cascade Mountains, consuming an estimated 5.1 million tons of fuel. The average estimated fuel burned per acre in Oregon and Washington was 39.8 and 31.9 tons, respectively. However, these estimates of fuel burned are subject to significant error which must be considered before drawing conclusions about total pollutant emissions based on these figures. Of the 138,000 acres burned annually, 61 percent of the burning was carried out in National Forests. In terms of burning activity per 100 square miles of commercial forest land, the National Forests burned 765 acres per 100 square miles, which is in contrast to burning on state and private lands of 201 acres per 100 square miles.

Emissions from forestry burning are highly complex, consisting of hundreds of gaseous chemical compounds and particulates, which vary greatly in composition and physical properties. Total emissions and the relative abundance of the major effluents are dependent on fire behavior and fuel conditions. A number of the compounds emitted are photochemically reactive and thus the physical and chemical properties of smoke change with increasing residence time in the atmosphere. Fire behavior can be controlled or predetermined within limits during prescribed forestry burning because such burning is carried out only under favorable fuel moisture and weather conditions. While these factors provide greater emissions predictability than is possible for wildfires, each fire has a unique emission profile.

Emission factors, relating quantity of effluent released to mass of fuel consumed, have been derived through laboratory burning studies and a limited number of field measurements. Laboratory measurements of emissions from burning forest fuels can be made fairly easily and represent the most practical approach for identification of fuel and fire parameters which govern emission production. However, unavoidable differences between laboratory and field situations, with respect to fire behavior and fuel conditions, must be considered when extrapolating laboratory-derived emission factors to field fires. Differences in fuel, fire behavior and burning techniques produce widely different emission patterns and use of a single emission factor for a given effluent is unrealistic. The following emission ranges for the major effluents were suggested by leading experts in forestry burning and represent the best general estimate of expected normal field emissions which can be made from data available at the present time:

Carbon dioxide (CO_2)	2000-3500	lb/ton of fuel
Water (H_2O)	500-1500	lb/ton of fuel
Carbon monoxide (CO)	20-500	lb/ton of fuel
Particulates (TSP)	17-67	lb/ton of fuel
Hydrocarbons (HC)	10-40	lb/ton of fuel
Nitrogen oxides (NO_x)	2-6	lb/ton of fuel.

These emission ranges apply to prescribed fires, which typically consume dry, dead fuels under conditions which tend to minimize emissions. Wildfires are generally fast moving headfires, which ignite both live and dead fuels in the fire front and leave a major portion of the available fuel to burn by smoldering. These conditions tend to maximize emissions. Estimates of total emissions from forestry burning are highly uncertain. Emission factor variations, magnified by uncertainties in estimating available fuel, result in calculated total emissions that may vary more than the range of emission factors.

In Oregon and Washington, air quality problems exist in many urban areas relative to primary and secondary National Ambient Air Quality Standards (NAAQS). Forestry burning is one potentially significant pollution source which may contribute to exceedances of the NAAQS in populated areas. Actual impact depends upon the composition of the plume and how the initial plume characteristics, the meteorology and the terrain affect the transport, dispersion, deposition and transformation of the plume. The impact of forestry burning upon air quality can be assessed through the use of mathematical models which describe emission patterns in relation to observed airflow patterns. Further assessment can be made by relating burning activities to pollution measurements with statistical or morphological correlations.

The available literature does not reveal any modeling studies that specifically determine the impact of slash burning activities on the smoke-sensitive regions of the Pacific Northwest. However, validation of models developed in other regions is being pursued in Oregon and Washington. Some research has been done using tracer materials to determine mass and momentum transport and dispersion into and within a forest canopy to help evaluate the impact of drift smoke. Most recently, a microscopical analysis of hi-vol filters and a multiple regression analysis of the data have been done in Oregon to assess the contribution of field burning and forestry burning to observed air quality levels. These preliminary studies indicate that forestry burning does have a significant, detrimental impact on observed particulate air quality measures.

Available data show no direct evidence of adverse health impacts from forestry burning in the Pacific Northwest. However, forestry burning has been shown to be a significant source of particulates, hydrocarbons and carbon monoxide emissions and may contribute to violations of health-related ambient air quality standards. Smoke intrusions into urban areas add to the particulate haze resulting from industrial and transportation source emissions. Forestry burning may not impact on air quality in areas where smoke is successfully vented away by smoke management programs.

Currently, both Washington and Oregon have smoke management programs designed to limit the air quality impact of forestry burning activities. The effectiveness of these programs has resulted in decreased citizen complaints related to forestry burning. The percentage of problem burns in Oregon between 1975 and 1977 averaged only 1.9 percent. In Washington, problem burns reported for 1977 were less than 1 percent of total burns. Monthly data did reveal that there are relatively high rates of problem burns occurring from July through September.

Alternative burning techniques and alternatives to burning which could be utilized to reduce impacts on air quality are available. However, as is the case with prescribed burning, a site-by-site evaluation is required to determine the applicability of these alternatives. Alternative burning techniques include the use of varying burn periods, optimal field procedures and the development and use of new burning technology. Nonburning alternatives include the use of mechanical or chemical treatments, improved harvesting systems, slash utilization or no treatment.

The future impact of forestry burning on air quality in the Pacific Northwest is a function of the level of burning, of Federal, state and local air quality regulations, and of the use of alternatives to burning. Recent data appear to indicate a downward trend in the amount of slash burned per acre on a regionwide basis. This coincides logically with increasingly better harvesting practices and wood fiber utilization. These trends, along with present smoke management programs and the federally mandated Clean Air Act, will most likely continue to reduce forestry burning activities.

The full impact of forestry burning on air quality in the Pacific Northwest is not accurately known at this time, although preliminary studies have indicated that the impact may be significant. To assess this impact and to minimize the future impact of forestry burning on air quality, a broad-scope, fully coordinated program, designed specifically to evaluate emissions, atmospheric dispersion characteristics, air quality impacts, and the economics of alternatives, is recommended. This program should utilize the resources of state, local and Federal agencies and forest industries and should draw on current significant research which is underway. The emphasis of this program should be the accurate evaluation of the air quality impact of forestry burning and the development of recommendations for reducing this impact to acceptable levels, through the use of alternatives to forestry burning, improved smoke management practices, and techniques for the reduction of emissions from burning.

CONTENTS

Executive Summary....iii
Figures....ix
Tables....xi
Acknowledgments....xiii
Project Staff....xiv

1. Introduction....1
    - Definition of terms....1
    - General background....10
    - Reasons for burning....18
    - Burning techniques....28
    - Prescribed fire in forest management - overview....35

2. Forestry Burning in Washington and Oregon....44
    - Location of forestry burns....44
    - Timber harvest activity and its relation to forestry burning....57

3. Emissions from Forestry Burning....58
    - Introduction....58
    - Major constituents of emissions....63
    - Other constituents....76
    - Fuel combustion....80
    - Fuel moisture....82
    - Source strength....82

4. Impact of Forestry Burning Upon Air Quality....85
    - Current air quality problems in the Northwest....85
    - Mechanisms by which forestry burning impacts air quality....89
    - Evaluation of the impacts of forestry burning....94
    - Relative impact of forestry burning....102

5. Methods of Reducing the Air Quality Impact of Forestry Burning....106
    - Smoke management programs--current programs in Washington and Oregon....106
    - Alternative burning techniques....116
    - Alternatives to forestry burning....123
    - The economics of forestry burning....143

6. Future Impact of Forestry Burning on Air Quality....152
    - Impacts of projected trends in burning....152
    - Impact of air quality regulations....157
    - Impact of alternatives to burning....159

CONTENTS (cont'd)

7. Requirements for Impact Assessment and Control....161
  Organizational needs....162
  Research needs....164
  Health effects studies....168
  Research in progress....169

Appendices

A. Tree species....173
B. Phase II - Economic Approach, Study Plan....174
C. Bibliography....176
D. Listing of Field Experts....241

FIGURES

Number Page

1 Physiographic subregion of the Pacific Northwest................11

2 Mean annual precipitation patterns of the Pacific Northwest......13

3 Forest zones of the Pacific Northwest............................14

4 Potential impact areas in Washington and Oregon..................16

5 Looking onto Penrold Mountain....................................22

6 Incomplete combustion temperature profile of pile or broadcast burn...34

7 Number of burns, western Washington and Oregon, 1975-1977........48

8 Acres burned, western Washington and Oregon, 1975-1977...........49

9 Estimated tons of fuel burned, western Washington and Oregon, 1975-1977..50

10 Land ownership in western Oregon and Washington..................53

11 Chromatogram of organic vapors in loblolly pine smoke............68

12 Nephelometer trace through plume.................................74

13 Nephelometer readings with respect to time.......................74

14 Vertical profile of smoke density................................90

15 Plume penetrating through top of mixing layer....................92

16 Common mesoscale and local afternoon dispersion conditions west of the Cascades during the warm season................95

17 Common nighttime or early morning condition during the warm season west of the Cascades................................95

18 Wind profile of forest on flat terrain...........................97

19 Wind profile of forest on sloping terrain........................97

20 Designated areas under Washington's and Oregon's Smoke Management Programs..107

21 Principle of air curtain combustion.............................121

FIGURES (cont'd)

Number Page

22 Alternatives to forestry burning....124

23 Energy consumption by the pulp and paper industry of the Pacific Northwest....140

24 Trend of acres burned on the West Side from 1972-77....153

25 Trend of tons burned on the West Side from 1972-77....154

26 Trend of tons/acre burned on the West Side from 1972-77....155

27 Three-year trend of broadcast and pile burning in Oregon....156

28 Program structure....163

29 Impact assessment....165

TABLES

Number Page

1 Prescribed Burning Ignition Devices.....30

2 Brown and Burn Herbicides and Desiccants.....32

3 Summary of Forestry Burning Activity in Washington and Oregon, 1975-1977.....45

4 Area of Commercial Timberland by Ownership Class.....52

5 Summary of Timber Production by Type of Tree.....55

6 Annual Forest Fire Particulate Production.....59

7 Particulate Emission Factors.....63

8 Emission Ranges.....64

9 Estimated Emissions Due to Forestry Burning, 1977, in Washington.....65

10 Estimated Emissions Due to Forestry Burning, 1977, in Oregon.....66

11 Particulate Emissions from Logging Slash.....72

12 PPOM from Burning Pine Needles by Fire Type.....78

13 PPOM from Burning Pine Needles by Fire Phases.....79

14 Trace Metal Emissions from Laboratory Burns of Sugar Cane.....80

15 National Ambient Air Quality Standards.....86

16 NAAQS Attainment Status for Oregon and Washington.....87

17 Statewide Emissions for Oregon and Washington.....104

18 Summary of Smoke Management Plan Restrictions for Washington and Oregon.....109

TABLES (cont'd)

Number Page

19 Percent Problem Burn Acreage by Month for 1975 Through 1977....113

20 Water Repellent Slash Coatings................................118

21 Average Size of Problem Broadcast Burns.......................120

22 Air Curtain Burners Operating Capacity........................122

23 Mechanical Slash Treatment Techniques.........................126

24 Properties of Herbicides Used for Forest Vegetative Control...129

25 Wood Products from Slash......................................137

26 Heat Values of Various PNW Tree Species.......................139

27 Conversion of Slash Into Energy Products......................141

28 Natural Decay Process of Western Hemlock......................142

29 Cost Examples of Prescribed Burning Ignition Devices and Burning Techniques in the Pacific Northwest...............145

30 Cost Examples of Nonburning Techniques in the Pacific Northwest...148

31 Class I Areas in Oregon and Washington........................158

32 Sources of Wood Residue Materials Used for Wood Products in the PNW.......................................160

ACKNOWLEDGMENTS

The GEOMET staff sincerely appreciate the cooperation of the many field experts interviewed for this report. In addition, special thanks are extended to the following people for their monumental efforts which insured the production of a document of the highest possible technical quality.

David Bray, USEPA Region X, our EPA Task Manager, whose even-handed study approach, guidance and technical advice provided the backbone of this study.

The Steering Committee members who provided direction, reams of data and constructive critiques throughout this project are:

Robert Wilson, USEPA, Region X
Darrell Weaver, DOE, Washington
Al Hedin, DNR, Washington
Robert Lamb (formerly with USDA FS, Region 6)
Ralph Kunz, USDA FS, Region 6
Scott Freeburn, DEQ, Oregon
Stuart Wells, DOF, Oregon
Royce Cornelius, Weyerhaeuser Co.

The USDA FS staff who assisted in the coordination of our field activities and provided much technical information, advice and text review are:

Craig Chandler
Edward Clarke
John Dell
R.W. Johansen
Leonidas Lavdas
Charles McMahon
Ralph Nelson
Neil Paulson
John Pierovich
David Sandberg
William Shenk
James Torrence

Stewart Pickford, University of Washington, who gave advice and professional review of portions of this document.

PROJECT STAFF

Project Manager

Benjamin J. Mason

Principal Authors

Jonathan D. Cook
James H. Himel
Rudolph H. Moyer

Contributing Authors

Robert C. Koch
Kenneth E. Pickering
Philip Tedder
John R. Ward
Robert H. Woodward

Technical Review and Editing - GEOMET, Incorporated

Douglas J. Pelton
John L. Swift
James E. McFadden
Judy M. Thomas

Publications, Graphics, and Reproduction

Leonora L. Riley
Anna E. Strikis
Jo Ann R. Koffman
Jacquelyn G. Sanks
Efegenia G. Maxwell
Margaret M. Etzler
I. Lee Oden
Donald R. Cade
Sallie S. Morse
Graphics, Inc.

SECTION 1

INTRODUCTION

The objective of this study is to establish, within the limits of state-of-the-art techniques, the actual and potential air quality impact of prescribed forestry burning on forest lands within the states of Washington and Oregon with an emphasis on the region west of the Cascade Mountains. This document evaluates the past, present and expected future impact of forestry burning on ambient air quality, identifies alternative methods or alternatives to forestry burning which could reduce the impact on air quality and evalutes the technical and economic feasibility and effectiveness of each. Appropriate conclusions are drawn with regard to possible short- and long-range actions for minimizing the impact of prescribed forestry burning on air quality.

This study also establishes baseline information for describing the magnitude and impact of existing and projected future emissions from forestry burning in the states of Washington and Oregon.

DEFINITION OF TERMS AS USED IN THIS REPORT

ACB: Air Curtain Burner--slash burner utilizing high-velocity, forced-air circulation for rapid, complete combustion with insignificant visible atmospheric emissions.

aerosol: A colloidal system in which the dispersed phase is composed of either solid or liquid particles no greater than 1 micron in diameter, and in which the dispersion medium is some type of gas, usually air. Haze, most smokes, and some fogs and clouds may be regarded as aerosols.

air quality: Atmospheric properties with respect to the presence of pollutants which may impair health, visibility or general welfare.

allelopathy: Repressive effect of plants upon each other, exclusive of microorganisms, by metabolic products, exudates, and leachates.

area burning: See broadcast burn.*

---

* Underlined terms are defined elsewhere in this definition of terms listing.

area ignition: Fires set in many places throughout an area either simultaneously or in quick succession and spaced so that the entire area is rapidly covered with fire.

available fuel load: The fuel load that will be consumed in a fire under given conditions. Compare total fuel load.

backing fire: A prescribed fire or wildfire burning into or against the wind or down the slope without the aid of wind. Compare head fire.

BIA: Bureau of Indian Affairs.

board products: A wood-based panel manufactured from small wood material, usually sawdust or chips, agglomerated with an organic binder and compression. These include particleboard, fiberboard, flakeboard.

broadcast burn: Burning of slash over a contiguous treeless area using any of a number of ignition devices, burning patterns, and pretreatments. Compare pile burn, understory burn.

brown and burn: The application of chemical desiccants or herbicides prior to broadcast burning.

brush: Scrub vegetation and immature stands of tree species that do not produce merchantable timber.

brushfield: A more or less temporary vegetative type, primarily of shrub species, that occupies potential forest sites.

bucking: Sectioning of log to desired lengths for optimum handling and utilization.

burning block: An area to be broadcast or understory burned as a unit within one daily work period.

burying: A residue disposal treatment in which residue is collected, placed in a large pit or trench, and covered with soil; usually done with a tractor.

cable yarding: A logging technique to move logs to a loading area using cables extending into a logging area from a stationary power unit. May include use of skyline cable system, helicopter or balloon.

chipping: (1) In residue treatment, the reduction of woody residue by a portable chipper to chips that are left to decay on the forest floor. (2) In utilization, the conversion of usable wood to chips, often at the logging site, for use in manufacture of pulp, hardboard, energy, etc.

clearcutting: A harvest and regeneration system, normally applied to an even-aged forest, whereby all trees are cut. Regeneration may be artificial or natural, logging methods may vary, and clearcut areas may be of any size.

commercial forest land: Land capable of or producing crops of industrial wood and not withdrawn from timber utilization. Productivity in excess of 20 ft^3/acre/yr (1.4 m^3/ha/yr) of industrial wood. Compare forest land.

controlled burning: See prescribed burning.

convection: The transmission of heat by the mass movement of heated particles, as circulation in air, gas, or liquid currents. In meteorology, convection refers to the thermally induced, vertical motion of air.

convective plume height: The elevation a plume attains due to buoyancy caused by its initial increased temperature over ambient conditions.

convective smoke column: The thermally produced ascending column of hot gases and smoke over a fire.

dbh: Diameter breast height, the diameter measurement of a standing tree 4-1/2 feet above ground level.

DEQ: Department of Environmental Quality, State of Oregon.

desiccant: A drying agent that kills tissues of living plants and causes them to lose moisture and dry out. Compare herbicide.

designated area: Areas designated by the Smoke Management Programs as principal population centers.

DOE: Department of Ecology, State of Washington.

duff: Forest litter and other organic debris in various stages of decomposition, on top of the mineral soil, typical of coniferous forests in cool climates where rate of decomposition is low and litter accumulation exceeds decay.

emission factors: Statistical average of the amount of emissions released to the atmosphere in relation to the amount of fuel burned. It is generally expressed in lbs/ton.

emission rate: An estimate of the amount of emissions released over time. It is generally expressed in lbs/hr.

emissions: Gases and particles which are put into the atmosphere by forestry burning.

fine fuels: The complex of living and dead herbaceous plants and dead woody plant materials less than 1/4 inch (0.6 cm) in diameter.

fire behavior: The response of fire to its environment of fuel, weather, and terrain including its ignition, spread, and development of other phenomena such as turbulent and convective winds and mass gas combustion.

firebreak: A natural or constructed strip or zone from which all fuels have been removed for the purpose of stopping the spread of fire or providing a control line from which to attack a fire.

fire climax: A plant association, forest type, or cover type held at a seral stage by periodic fires, therefore differing from the true climax community; e.g., a Douglas-fir forest in the western hemlock zone.

fire danger: Resultant of both constant and variable factors--weather, slope, fuel, and risk--that affect the inception, spread, and difficulty of control of fires and the damage they cause.

fire hazard: The probability that a fuel complex defined by kind, arrangement, volume, condition and location will form a special threat of ignition, spread, and difficulty of suppression.

fire hazard reduction: Any residue treatment that reduces threat of ignition, spread of fire, and its resistance to control. This may involve removal, burning, rearrangement, burying, or modification such as by masticating or chipping.

fire retardant: Any substance that reduces flammability by chemical or physical action.

fire risk: The chance of a fire starting as determined by the presence and activity of causative agents; usually divided into man-caused risk and lightning risk.

fire season: The portion of the year during which fires are likely to occur, spread, and do sufficient damage to warrant organized fire control; strongly dependent on climate.

fire storm: An extremely intense fire drawing in surrounding gases and creating a strong vertical convective plume.

flash fuels: Fuels such as dried grass, leaves, dried pine needles, dead fern, tree moss, and some kinds of slash which ignite readily and are consumed rapidly when dry. Compare heavy fuels.

forest land: Land at least 10 percent occupied by forest trees of any size, or formerly having had such tree cover, and not currently developed for nonforest use. Compare commercial forest land.

forestry burning: See prescribed burning.

fuel loading: The amount of fuel present expressed quantitatively in terms of weight of fuel per unit area. This may be available fuel or total fuel and is usually dry weight.

fuel moisture content: The quantity of water in a fuel particle expressed as a percent of the oven dry weight of the fuel particle.

Gaussian plume: A plume in which the concentration of the pollutant material is distributed according to the normal distribution (the fundamental frequency distribution of statistical analysis) in the crosswind and vertical directions.

hazard reduction: Factors which may reduce fire hazard.

head fire: A fire spreading or set to spread with the wind and/or upslope. Also heading fire. Compare backing fire.

head of fire: The most rapidly spreading portion of a fire's perimeter, usually to the leeward or upslope.

heavy fuels: Fuels of large diameter such as snags, logs, and large limbwood that ignite and are consumed more slowly than flash fuels.

herbicide: A chemical compound that causes physiological plant damage usually resulting in death.

high-lead yarding: A method in which logs are dragged to the loading area by cable, usually in contact with the ground. Compare cable yarding.

HLS: High Lead Scarification--cable scarification technique using a drum or other heavy object to break up slash continuity and expose soil.

humus: That more or less stable fraction of the soil organic matter remaining after the major portion of plant and animal residues have decomposed; usually dark colored.

hydrocarbon: The simplest organic compounds composed of hydrogen and carbon. Hydrocarbons include gases, liquids, and solids and vary from simple to complex molecules. They are divided into alkanes or saturated hydrocarbons, cycloalkanes, alkenes or olefins, alkynes or acetylenes, and aromatic hydrocarbons.

intensity: The rate of heat release per unit length of fire front. Generally expressed in BTU/sec ft.

inversion (temperature inversion): A layer through which temperature increases with altitude; e.g., nighttime inversion above the ground. Aloft, an inversion layer separates warmer air above from cooler air below. This most stable condition inhibits vertical motion of air.

ITF-FSU: Interim Task Force on Forest Slash Utilization, Senator John Powell, Chairman, State of Oregon, 1977.

ladder fuels: Provide vertical fuel continuity between strata as between surface fuels and crowns.

landing: Anyplace on or adjacent to the logging site where logs are assembled for further transport. See yarding.

lee waves: An airflow pattern that develops on the downwind side of mountainous terrain.

light burn: Degree of burn which leaves the soil covered with partially charred organic material; large fuels are not deeply charred. Compare severe burn.

litter: The surface layer of the forest floor consisting of freshly fallen leaves, needles, twigs, stems, bark, and fruits. This layer may be very thin or absent during the growing season.

logging residue: Unmerchantable or otherwise unwanted woody material remaining after a logging operation.

lopping: Cutting branches, tops, and small trees after felling, so that the resultant slash will lie close to the ground. To cut limbs from felled trees.

masticating: Breaking and crushing of residue in place with heavy equipment including tractors and weighted rollers with cutting devices. Usually limited to brush, thinnings, and small slash. Serves to lower height of fuel and enhance its decay by increasing contact with the soil.

mixing layer: The surface layer of the atmosphere which is relatively unstable compared with air at higher altitudes. The layer is strongly influenced by the frictional and radiative effects of the earth's surface.

NFDRS: National Fire Danger Rating System.

(O.D.) tons: Oven dried ton--2,000 pounds of fiberwood dried to a constant weight at 105° C.

old growth: Timber stands of age and stature so as to resemble a "virgin" forest in which the mean annual growth is declining.

old-growth stand: Loosely defined as a condition in which rate of tree growth has passed its peak and normal processes of deterioration approach or exceed stand growth.

OSMS: Oregon Smoke Management System.

PAM: Per Area Material--standard merchantable material measured per acre area.

particulates: A component of polluted air consisting of any liquid or solid particles suspended in or falling through the atmosphere. Particulates are responsible for the visible forms of air pollution.

PF: Phenolformaldehyde--an organic binding agent for wood products.

pile burn: Burning of slash piled by PUM or YUM techniques. See PUM or YUM. Compare broadcast burn.

plume: A cloud of pollutant material, containing emissions from a particular source or group of sources, which is being dispersed in the atmosphere.

PM: Per thousand material--standard merchantable material measured per acre area.

prescribed burning: The intentional ignition of grass, shrubs, or forest fuels under weather and fuel conditions that will confine the fire to a predetermined area and produce the intensity of heat and rate of spread required to accomplish planned forest management benefits including hazard reduction, silvicultural and range improvement.

problem burn: Within the context of the Oregon Smoke Management Program, a burn whose smoke plume intrudes into a designated area.

PUM: Piling Unmerchantable Material by hand or tractor in partially cut, thinned, clearcut or right-of-way areas.

pyrolysis: Thermal decomposition of matter in the absence of oxygen.

pyrosynthesis: The synthesis of large molecules in the reducing region of the flame.

rate of spread: The relative activity of a fire in extending its horizontal dimensions. It may be expressed as rate of increase of the perimeter, as a rate of forward spread of the fire front, or as a rate of increase in area.

residence time: The time an emission component is in the air between emission and removal from the air or change into another chemical configuration.

residual smoke: Smoke produced after the initial fire has passed through the fuel.

roughwood: Wood chips made from unbarked material.

scarification: Loosening the top soil of open areas, or breaking up the forest floor in preparation for regenerating by direct seeding or natural seedfall. Done to reduce vegetative competition and to expose mineral soil.

second growth: Natural or planted timber stands on areas previously logged or cleared.

sere: One of a series of ecological communities succeeding one another in the biotic development of an area.

severe burn: Degree of burn in which all organic material is burned from the soil surface which is discolored by heat, usually to red. Organic matter below the surface is consumed or charred. Compare *light burn*.

silvicultural burning: See *prescribed burning*.

site: An area considered in terms of the type and quality of the vegetation the area can carry as indicated by its biotic, climatic, and soil conditions.

site preparation: Removal or killing of unwanted vegetation, residue, etc., by use of fire, herbicides, or mechanical treatments in preparation for reforestation and future management.

slash: A complex of woody forest debris left on the ground after logging, land clearing, thinning, pruning, brush removal, or natural processes such as ice or snow breakage, wind, and fire. Slash includes logs, chunks, bark, branches, tops, uprooted stumps and trees, intermixed understory vegetation, and other fuels.

slash and burn: Hand or mechanical cutting or impaction of slash material prior to broadcast burning.

slash burning: See *prescribed burning*.

smoke episode: A period when smoke is dense enough to be an unmistakable nuisance.

smoke management: A system whereby current and predicted weather information pertinent to fire behavior, smoke convection, and smoke plume movement and dispersal is used as a basis for scheduling the location, amount, and timing of burning operations so as to minimize total smoke production and assure that smoke does not contribute significantly to air pollution.

smoke-sensitive area: An area in which smoke from outside sources is intolerable, owing to heavy population, existing air pollution, or intensive recreation or tourist use.

smoldering combustion: Combustion of a solid fuel, generally with incandescence and smoke but without flame.

spotfire: A fire produced by sparks or embers that are carried by the wind beyond the zone of direct ignition by the main fire.

stability: The degree to which the vertical temperature structure of the atmosphere restricts the rising and dispersion of air pollutants.

synergism: Cooperative action of two or more chemicals so that their total effect is greater than the sum of their individual effects on the same organism.

thinning: To reduce the number of trees per acre so that residual tree growth will be enhanced.

total fuel load: The total quantity of inflammable material including slash, brush, litter and duff on a given site, but not necessarily consumable. Generally expressed in tons/acre. Compare available fuel load.

understory burn: A prescribed burn of low intensity used in forested areas to achieve treatment objectives without damaging desirable vegetation.

USEPA: United States Environmental Protection Agency.

USDA-FS: United States Department of Agriculture-Forest Service.

USDOE: United States Department of Energy.

whole tree logging: Felling and transporting the whole tree without the stump, but with its own crown, for trimming and bucking at a landing or mill.

wildfire: An unplanned fire, not being used as a tool in forest protection or management in accordance with an authorized permit or plan, which requires suppression.

yarding: Moving of logs from stump to roadside deck or landing.

YUM: Yarding Unmerchantable Material by cable techniques, usually in areas inaccessible to tractors.

GENERAL BACKGROUND

Characterization of the Study Area

This study describes aspects of prescribed forestry burning and its impacts in the Pacific Northwest region of the United States, encompassing the 165,173 square-mile area of the states of Washington and Oregon. The region has two study areas (see Figure 1):

1. West Side--West of the Cascade divide to the Pacific Ocean
2. East Side--East of the Cascade divide to the Idaho border.

West Side--

Physiography--The physiographic subregions of the West Side according to Franklin and Dyrness (1973) are:

- West Slopes of the Cascades--Glacier-formed valleys characterize the west slopes of the Cascades. The ridge-top elevation gradually decreases from approximately 2500 m in the north to approximately 1880 m in the south. Mt. Rainer (elevation 4420 m) in Washington and Mt. Hood (elevation 3440 m) in Oregon are two of the highest peaks in the Cascades.

- Puget Trough--The Puget Trough is situated to the west of the Cascades in Washington and includes the Puget Sound in the north and the Cowlitz and Chehalis River Valleys in the south. Inlets and islands characterize the glaciated Puget Sound area. Elevations in the southern portion of the Puget Trough seldom exceed 160 m.

- Willamette Valley--The Willamette Valley, south of the Columbia River, is an extension of the Puget Trough. This subregion is characterized by broad valleys with low, intermittent hills. The average elevation gradually increases towards the south and ends where the Cascades and Coast Ranges converge in southern Oregon.

- Olympic Peninsula--The Olympic Peninsula includes the Olympic Mountains and bordering flatlands. The Olympic Mountain Range contains peaks up to 2420 m in elevation although most ridge tops average around 1300 m.

- Coast Ranges--The Coast Ranges are located west of the Willamette Valley and Puget Trough. It is an area of steep slopes and abrupt ridges, especially in the southern part. The average elevation of the ridge line is approximately 600 m with the elevation of the highest peak at 1249 m. Mountain passes lead to the Pacific Coast.

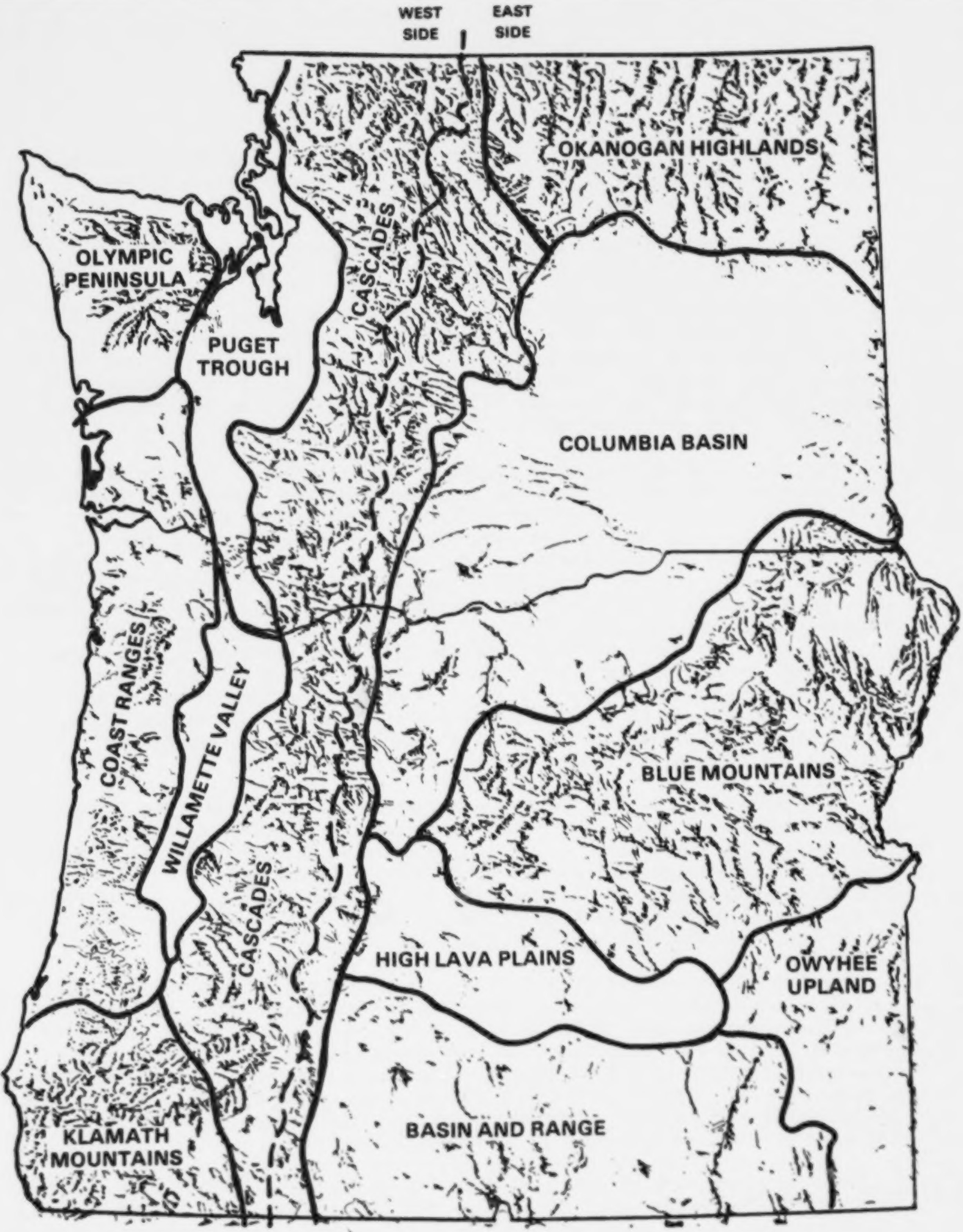

WEST SIDE
EAST SIDE
OKANOGAN HIGHLANDS
OLYMPIC PENINSULA
CASCADES
PUGET TROUGH
COLUMBIA BASIN
COAST RANGES
WILLAMETTE VALLEY
BLUE MOUNTAINS
CASCADES
HIGH LAVA PLAINS
OWYHEE UPLAND
KLAMATH MOUNTAINS
BASIN AND RANGE

Figure 1. Physiographic subregion of the Pacific Northwest.

- Klamath Mountains--The Klamath Mountains are in southwest Oregon. The average elevation of the ridge line is approximately 900 m with the highest peak at 2280 m.

Climate--The West Side has a maritime-type climate characterized by fairly dry summers and mild, wet winters.

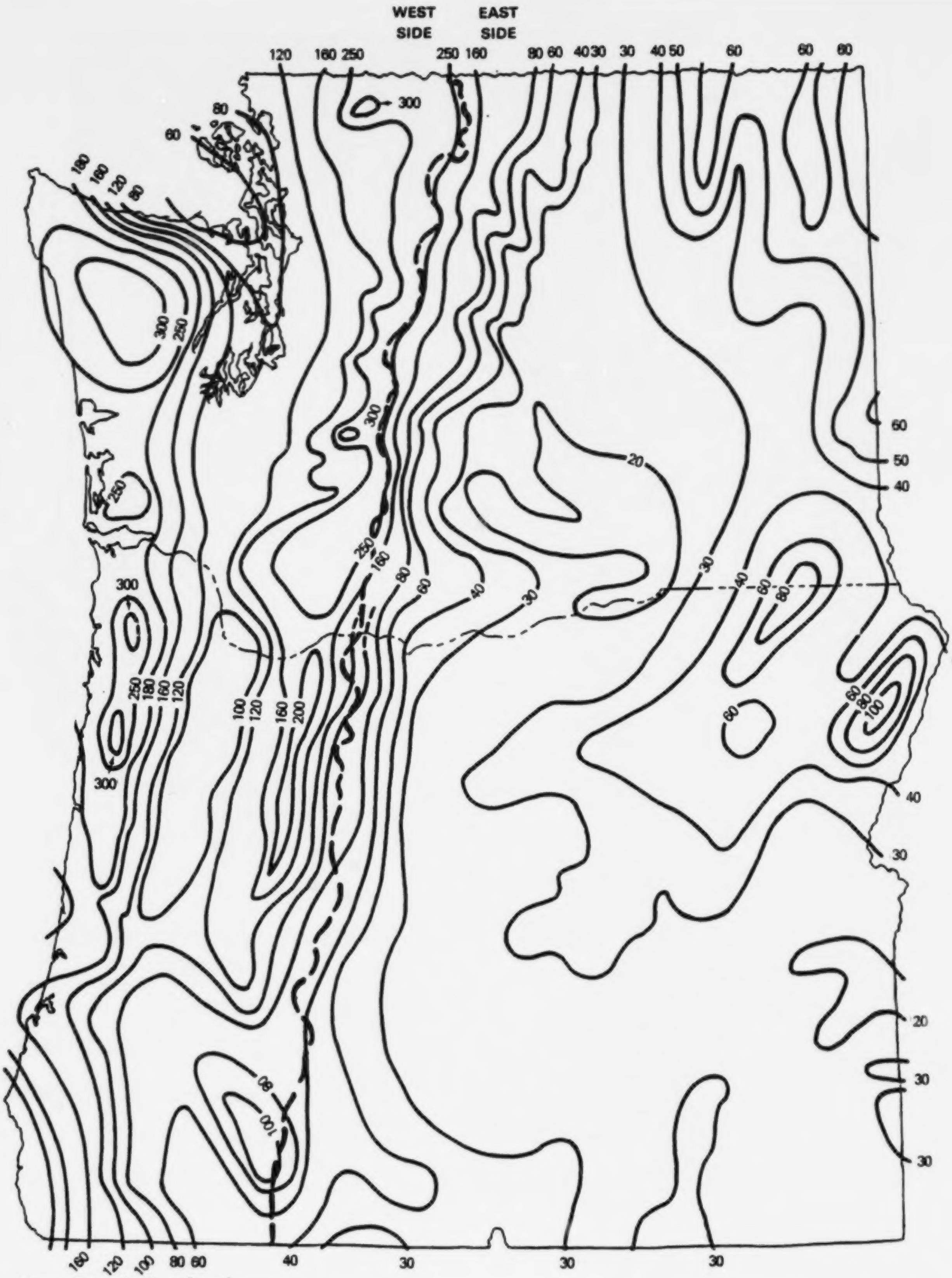
The relatively small variation in seasonal temperatures on the West Side may be attributed to the proximity of the Pacific Ocean and the Cascade Ranges. Seasonal temperature variations in the Pacific Ocean are small compared to the North American continent. The prevailing westerlies advect these moderating temperatures inland. The Cascades shield the West Side from cold continental air masses in the winter and hot air masses in the summer.

The precipitation pattern of the West Side, in Figure 2, is a product of meteorological and topographical factors. According to Franklin and Dyrness (1973), up to 85 percent of the precipitation falls between October 1 and April 1. This is due to the north-south migration of the Pacific high and the semipermanent low pressure cell found over the northern Pacific. During the winter months this cell intensifies and moves southward causing the storm track to be centered over the Pacific Northwest. The Klamath Mountains, Olympic Mountains, Cascades, and Coast Ranges also affect precipitation. The prevailing westerlies carry the moist Pacific air inland where it is lifted over the ranges, cooled, and condensed. This moisture is precipitated on the western slopes and higher peaks of these mountains producing an annual precipitation of 300 cm. A rain shadow exists in the Willamette Valley, Puget Trough, and river valleys of the Klamath Mountains due to the westerlies subsiding on the eastern slopes of the coastal mountains.

Stable atmospheric conditions are frequently found in the Puget Trough-Willamette Valley region. These conditions are formed by radiational cooling, subsidence, or a combination of the two. Inversions are also induced by warm advection over a topographically trapped, surface-based layer of cold air. Inversion-level heights are variable and are dependent upon the relative degree of cooling and adiabatic warming of the air mass due to subsidence. These conditions occur most frequently in the fall.

Graham (1953) reports that a natural pressure gradient wind funnel exists in the Columbia Gorge between the West Side and the East Side. The Columbia River flows through this narrow opening in the Cascade Range. The gorge provides an opening for the movement of continental air into the Puget Trough-Willamette Valley area and likewise for the movement of maritime air into the Columbia Basin. Dry continental air moving westward through the gorge produces an increased fire danger. Other areas west of the Cascades are similarly affected by westward movements of continental air.

Forest zones--The West Side is occupied by four major forest zones. Figure 3 shows the predominant tree species expected in each zone. Situations may exist in these forest zones where large stands of subclimax tree species such as red alder or plupiographic climax stands of trees such as western red cedar are present. A complete list of West Side tree species is included in Appendix A.


WEST SIDE
EAST SIDE
120
160
250
250
160
80
60
40
30
30
40
50
60
60
60
300
80
60
180
160
120
80
300
250
300
250
20
60
50
40
250
180
160
80
60
40
30
30
40
60
80
40
300
250
180
160
120
100
120
160
200
60
80
100
60
40
30
300
20
30
30
80
100
160
120
100
80
60
40
30
30
30

Note: Precipitation given in cm.

Figure 2. Mean annual precipitation patterns of the Pacific Northwest.

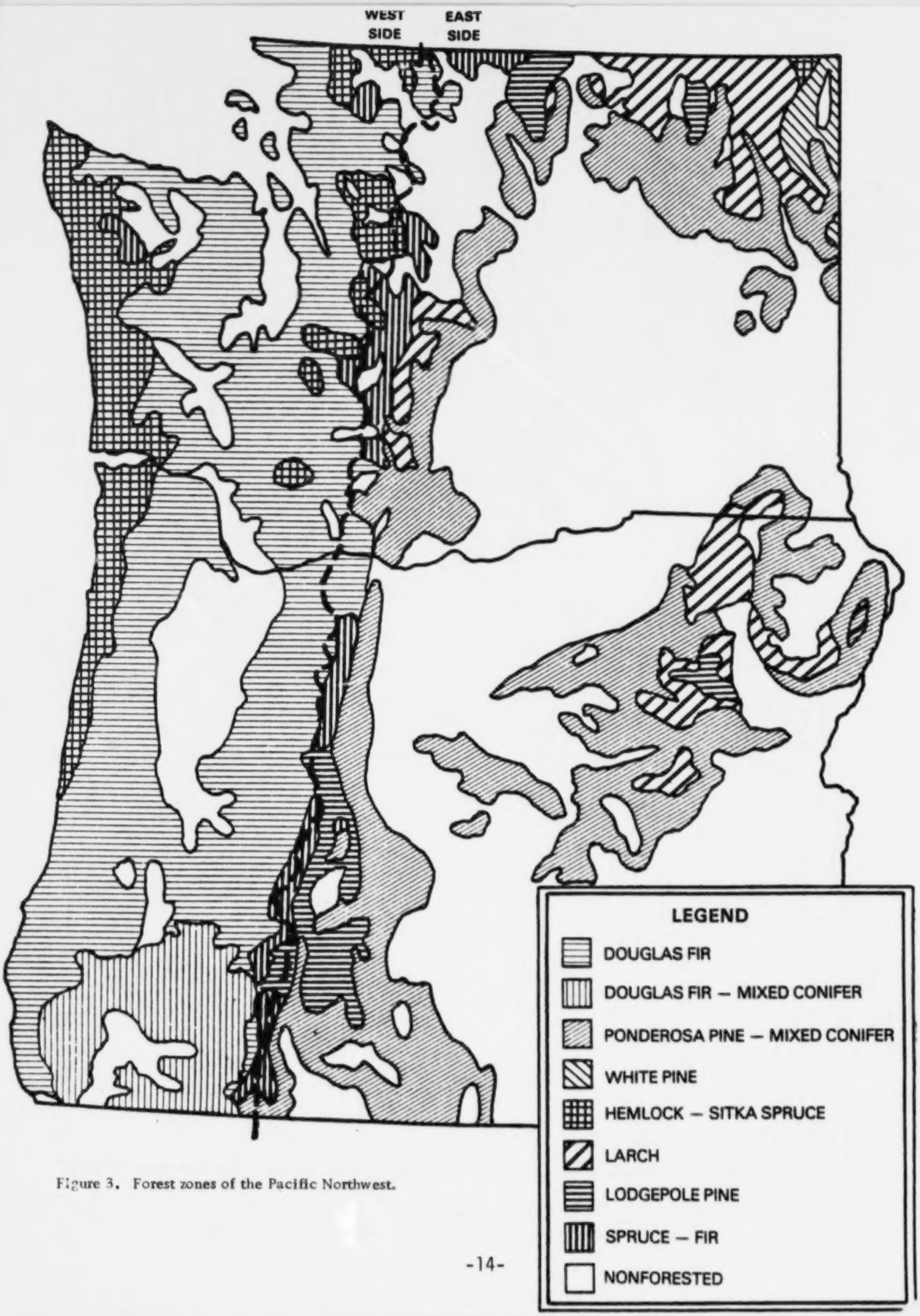

WEST SIDE
EAST SIDE
LEGEND
DOUGLAS FIR
DOUGLAS FIR — MIXED CONIFER
PONDEROSA PINE — MIXED CONIFER
WHITE PINE
HEMLOCK — SITKA SPRUCE
LARCH
LODGEPOLE PINE
SPRUCE — FIR
NONFORESTED

Figure 3. Forest zones of the Pacific Northwest.

- Douglas-fir--Douglas-fir (Pseudotsuga menziesii) occupies much of the Coast Range, Olympic Peninsula, Puget Trough, and the western slopes of the Cascades. Associated species may include western hemlock (Tsuga heterophylla), sitka spruce (Picea sitchenis), ponderosa pine (Pinus ponderosa), and western red cedar (Thuja plicata). Douglas-fir is commonly found in pure stands. Red alder (Alnus rubra) often inhabits recently disturbed areas. The understory contains a large array of shrubs and herbs.

- Douglas-fir - Mixed Conifer--Douglas-fir and mixed conifers are found in the interior Klamath Mountain Range. This zone has a variety of tree species including Douglas-fir, ponderosa pine, tan oak (Lithocarpus densiflorus), sugar pine (Pinus lambertiana), incense cedar (Libocedrus decurrens), and white fir (Abies concolor).

- Hemlock - Sitka Spruce--Western hemlock and sitka spruce are found along the coastal plains of the Pacific Coast and in some areas of the Coast Range and western slopes of the Cascades. Associated species may include western red cedar, Douglas-fir, grand fir (Abies grandis), and red alder. The understory may contain a dense growth of shrubs and ferns.

- Spruce - Fir--Mixed spruce and fir are found along the crest of the Cascades. This zone has a variety of tree species including Pacific silver fir (Abies amabilis), noble fir (Abies procera), western hemlock, Engelmann spruce (Picea engelmannii) and subalpine fir (Abies lasiocarpa). The understory may consist of large shrubs, herbs or moss.

Potential impact areas--The potential impact areas on the West Side considered in this study include population centers and recreation and wilderness areas. Most of the West Side population centers are situated in the Willamette Valley-Puget Trough area. Recreation and wilderness areas are scattered throughout the region (Figure 4).

East Side--

Physiography--Figure 1 (shown previously) illustrates the physiographical subregions of the East side.

The three major mountain systems found on the East Side are the eastern Cascades, the Okanogan Highlands, and the Blue Mountains. The elevation of the Cascades gradually decreases from 2500 m in northern Washington to approximately 1880 m in southern Oregon. Higher peaks such as Mr. Rainer (elevation 4420 m) and Mt. Hood (elevation 3440 m) protrude above the ridge-top. The Okanogan Highlands, located in northeast Washington, are characterized by rounded ridge tops with elevations up to 2400 m. The Blue Mountains in northeast Oregon and southwest Washington contain several ranges with peaks reaching 2900 m in elevation.

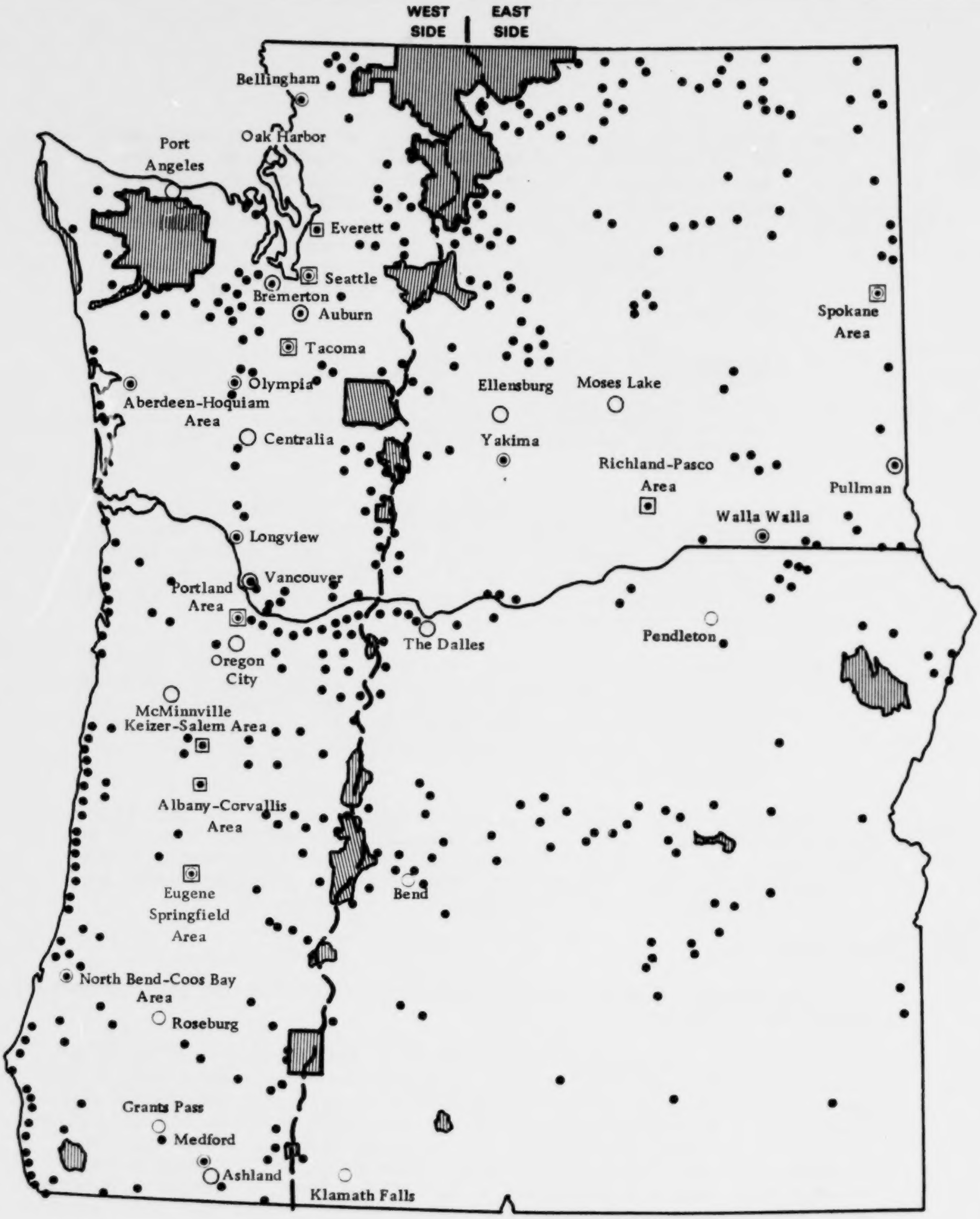

WEST SIDE
EAST SIDE
Bellingham
Port Angeles
Oak Harbor
Everett
Seattle
Bremerton
Auburn
Tacoma
Spokane Area
Olympia
Aberdeen-Hoquiam Area
Ellensburg
Moses Lake
Centralia
Yakima
Richland-Pasco Area
Pullman
Walla Walla
Longview
Vancouver
Portland Area
The Dalles
Pendleton
Oregon City
McMinnville
Keizer-Salem Area
Albany-Corvallis Area
Bend
Eugene Springfield Area
North Bend-Coos Bay Area
Roseburg
Grants Pass
Medford
Ashland
Klamath Falls
CITIES
Population (x1000)
▣ >100
▣ 50-100
◉ 20-50
○ 10-20
● WINTER SPORTS AREAS
CAMPSITES
STATE PARKS
ROADSIDE PARKS
▨ NATIONAL PARKS & WILDERNESS AREAS

Figure 4. Potential impact areas in Washington and Oregon.

The remaining subregions consist of plateaus, rounded ridges and broad valleys. The Columbia Basin is characterized by rolling hills ranging from 300 to 600 m in elevation. The High Lava Plains contain volcanic formations from lava flows as recent as 2000 B.C. The average elevation is 1200 m. The Basin and Range and the Owyhee Uplands average 1200 m in elevation with isolated fault-block mountains attaining elevations of 2900 m.

Climate--The East Side climate is affected by the proximity of the Pacific Ocean, Cascades, and Rocky Mountain Ranges. These geographic features allow both maritime and continental air masses to move into the region.

The precipitation pattern of the East Side is a product of several factors. The moist maritime air carried by westerlies loses much of its moisture on the Coast and Cascade Ranges. Clouds are further dissipated by subsidence west of the Cascades. This results in an annual precipitation of 20 to 40 cm in the lowlands. A local precipitation high of 100 cm per year in the Blue Mountains and 60 cm per year in the Okanogan Highlands is due to the lifting of these ridges.

The temperature regime of the East Side is governed in part by the Rockies and Cascades. The Rocky Mountains to the east and north shield this region from cold continental air masses in the winter. Likewise, the Cascades block milder air during the winter. The summer months are normally warm and dry. Extremes in temperatures occur during all seasons when the region is under the influence of continental air.

Forest zones--Figure 3 (shown previously on page 14) shows that East Side forests are predominantly found on the eastern Cascades, the eastern third of the High Lava Plains, the Basin and Range subregion, the Okanogan Highlands, and the Blue Mountains. Elsewhere, forests are found only in river valleys and north-facing slopes.

The East Side is occupied by five major forest zones. East Side tree species may be found in Appendix A.

- Ponderosa pine - Mixed conifer--Ponderosa pine and mixed conifers occupy the eastern slopes of the Cascade Range, the south-central area of Oregon, and sections of the Blue Mountains and Okanogan Highlands. Associated species may include western juniper (Juniperus occidentalis), quaking aspen (Populus tremuloides), lodgepole pine (Pinus contorta), Oregon white oak (Quercus garryana), grand fir and the inner-mountain variety of Douglas-fir. The understory of ponderosa pine stands consists of shrubs and herbs.

- White pine--Western white pine (Pinus monticola) occupies an area in northeastern Washington in association with lodgepole pine, western larch (Larix occidentalis), and western hemlock.

- Larch--Western larch occupies large areas in the Blue Mountains of Oregon and the Okanogan Highlands of Washington. Associated species include ponderosa pine, Douglas-fir, and lodgepole pine.

- Lodgepole pine--Lodgepole pine occupies the eastern slopes of the Cascades in Oregon and as nearly pure stands in the Okanogan Highlands of Washington. Associated species include ponderosa pine, Douglas-fir, western hemlock and western larch.

- Spruce - Fir--Mixed spruce and fir are found along the crest of the Cascades. This zone has a variety of tree species including Pacific silver fir, noble fir, westen hemlock, Engelmann spruce and subalpine fir. The understory may consist of large shrubs, herbs or moss.

Potential impact areas--Potential impact areas are scattered throughout the East Side forest zones (Figure 4, page 16). Major recreation and wilderness areas include part of the North Cascades National Park, Crater Lake National Park, Ross Lake National Recreation Area, and all of Lake Chelan National Recreation Area.

REASONS FOR BURNING

Prescribed burning is used to reduce or eliminate unwanted natural and man-caused accumulations of slash, brush, litter or duff in a "controlled application" so as to maximize net benefits with minimum damage and at an acceptable cost (Williams 1975). Burning accomplishes three basic objectives:

1. To reduce the hazard of wildfire posed by excessive fuel accumulations

2. To aid in silvicultural activities

3. To improve grazing forage and wildlife habitat.

These objectives have long been associated with the timber-producing regions of the Southeastern United States. The use of prescribed fire in the timber-producing regions of Pacific Northwest is based on these same objectives, but in technique and applicability may be as highly variable as this region's vegetation, physiography and climate.

The appropriate use or nonuse of prescribed burning depends on an assessment of site-specific variables including:[1]

- Fuel Factors--Fuel type, size, arrangement, continuity, quantity, moisture; burning characteristics; associated vegetation; and adjacent fuel hazards (snags, private slash, flammable brushfields, etc.)

---

[1] Personal communication, J. Dell, USDA FS, November 29, 1977.

- Topographic Factors--Steepness of slope; irregularity of terrain (gullies, ridges, escarpments); elevation, and slope direction (aspect)

- Weather and Climatic Factors--Prevailing wind directions; vulnerability to high velocity east winds; smoke management restrictions (distance from designated smoke sensitive areas, local valley and canyon winds and their influence on smoke drift and persistence, temperature inversion patterns); allowable dry periods for burning; and fire weather severity

- Accessibility Factors--Drive-in or walk-in distance for preparation, burning, holding, and mop-up crews and their equipment; and unit access in relation to on-unit logging spurs, landings, natural barriers, etc.

- Manpower and Management Factors--Restrictions and ceilings on manpower available to do the job; support costs (clerical and business management, transportation, equipment, communications, etc.); and size of unit.

Factors which may necessitate the use of prescribed burning instead of mechanical treatment include steep slopes that are greater than 30 percent and are not feasible for mechanical treatment, fragile soils which may be highly erodible if mechanically disturbed, and other environmental factors for which fire may cause the least impact of available methods.

Hazard Reduction

A general concern for the threat of catastrophic wildfires in the heavily forested areas of Washington and Oregon has resulted in extensive fire suppression activities since 1910. Recent research indicates that past suppression activities and inadequate fuel management programs have enhanced the threat of wildfires by allowing fuel loads in the forest to accumulate to unnaturally high levels (Davis and Cooper 1963, Vogl 1971, Hall 1977). The presence of heavy untreated slash concentrations in old-growth forests has been attributed with enhancing the spread of major wildfires in recent years, including the Tillamook, Oxbow and Wenatchee-Okanogan fires. Between 1973 and 1977, 44 percent of the wildfires on DNR-protected lands in Washington started in logging and thinning slash.[2]

---

[2] Personal communication, A. Hedin, Washington Department of Natural Resources, April 21, 1978.

In an assessment of what can be done to reduce the number of destructive forest fires, Wilson and Dell (1971) point out that of the three major factors which influence wildfire behavior - atmospheric conditions, topography and fuel loads - we can modify only fuels loading.

Effective fuels management through fuel modification over vast areas is not presently feasible, however, periodic precribed burning can be used to create and maintain fuel breaks by removing dead fuels and highly flammable understory vegetation. Roe et al. (1971) contend that judicious use of prescribed burning can reduce the occurrence of costly and uncontrollable catastrophic wildfires. Burning will commonly dispose of fuel under 2 inches in diameter and sometimes all material under 4 inches in diameter, whereas increased utilization and cleaner logging techniques will not be as successful as burning for eliminating fine fuels (Smith 1962).

Measurements by Anderson, Fahnestock, Philpot and others[3] show that wildfire may temporarily increase available fuel by killing green vegetation, but that prescribed burning will reduce total available fuels, the rate of fire spread and the associated wildfire resistance to control. This is accomplished through the interruption of the horizontal and sometimes the vertical continuity of flammable materials by the reduction of highly inflammable fine fuels (Smith 1962). Hodgson 1968[4] showed that doubling the amount of fine fuels doubled the rate of fire spread and produced a fourfold increase in fire intensity.

West Side--

Prescribed burning is used on the West Side to eliminate logging activity residues from the clear cut harvesting of Douglas-fir or other species, which if not treated would remain a wildfire hazard for many years (Dell and Green 1968). Unutilized slash may accumulate to "total fuel" loads in excess of 50 tons per acre and can reach over 200 tons per acre in extreme cases (Dell and Ward 1972). Of this "total fuel" load the finer materials including foliage, twigs and small branches compose "available fuel" loads of from 20 to 40 tons per acre (Moore and Norris[5]). Martin et al. (1976) indicate that the upper limit of available fuel loads, above which fires were prone to "blow up" is between 5 and 7 tons per acre.

Fuel models of the mature West Side Douglas-fir timber type indicate that in 1 hour a wildfire in slash fuels will be four times the size of a fire burning in a natural fuel complex (Deeming et al. 1974). Evaluations of the 14 major wildfires which have occurred in the Mt. Hood National Forest during the period from 1960 to 1975 show that in each case, the fires either started or gained momentum in accumulated logging slash fuels (Dell 1977).

---

[3] As cited in Martin 1976.

[4] As cited in Dodge 1972.

[5] Contained in Cramer 1974.

In contrast, the understory of western red cedar-forested areas on the Olympic Peninsula are constantly wet and present very little wildfire hazard. Field observations by the BIA[6] indicate that slash beneath a forest canopy of this type will not support a ground fire because of the high moisture content of the fuel. Wildfires in this area are normally confined to clearings and along roads.

East side--

Catastrophic wildfires in East Side ponderosa pine forests may be reduced by restoring the natural component of periodic fire to the forest under controlled conditions (Biswell et al. 1973). Wildfire damage is reduced by understory burning in five principal ways:

1. Reducing the volume of dead, highly flammable fuels
2. Thinning dense thickets of pine saplings and pole-size trees
3. Raising the height of green tree foliage by needle scorching, thus decreasing the chance of vertical spread and crown fires
4. Eliminating understory trees, thus decreasing the chance of vertical spread.
5. Eliminating ground litter, therefore allowing close compaction of the subsequent needle-fall.

Studies by Weaver, Cooper, Biswell, Hall and others indicate that intervals of 5 to 10 years approximate the natural occurrence of fuel-reducing ground fires in ponderosa pine.

An example of the successful use of periodic understory burning to minimize wildfire damage was demonstrated during the Penrold Butte, Arizona wildfire of June 1963. Figure 5 shows a stand of trees which had been understory burned by prescription in 1956 and 1961 in which the wildfire was confined to the ground and did no damage. However, as shown in the foreground, where no previous understory burning had occurred, the wildfire killed 100 percent of the trees.

Kallander 1965[7] concluded that understory burning in ponderosa pine stands on the Fort Apache Indian Reservation, Arizona reduced the size of wildfires on treated areas by over 60 percent. Observations by Davis and Cooper (1963) showed that periodic prescribed burning in southern pine reduced the number, size, intensity and destructiveness of wildfires.

---

[6] Personal communication, R. French, Bureau of Indian Affairs, January 18, 1978.

[7] As cited in Biswell et al. 1973.

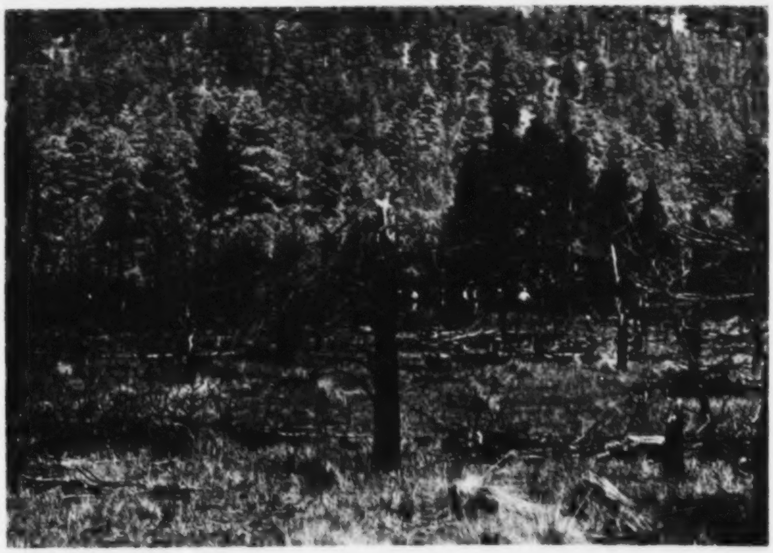


Figure 5. Looking onto Penrold Mountain where the Penrold Butte Wildfire of 1963 burned under the trees after two controlled burns, one in 1956 and the second in 1961. There the wildfire did no damage. In the foreground there had been no controlled burning and the wildfire killed all the trees, small and large. (Biswell et al. 1973)

In 1968, Fahnestock studied the wildfire hazard of slash from precommercial thinning of ponderosa pine on the Deschutes National Forest, Oregon. He found that thinning to an 18 x 18 foot spacing generated up to 40 tons of slash per acre. He concluded that this slash accumulation probably represented as great a fire damage hazard in this thinned stand as did the dense thicket prior to thinning.

In an earlier study, Weaver (1957)[8] showed that three successive understory burns on the Colville Indian Reservation, Washington reduced fuel loads from 21.5 tons per acre to 3 tons per acre.

Silvicultural

Historically, prescribed burning has been primarily used to reduce the threat of wildfire. However, recent figures in the Pacific Northwest indicate an increasing use of silvicultural burning (Oregon, State of 1977m).

---

[8] As cited in Biswell et al. 1973.

Silvicultural burning may be utilized for one or more of the following reasons:[9]

- To Reduce Undesirable Brush Growth Competition for Sunlight and Moisture--Unmerchantable brush species may occupy the growing space of desirable tree species and reduce potential yields. However, this same brush cover may provide essential protective shade for other desirable tree species (Jemison and Lowden[10]).

- To Remove Obstacles to Tree Planting, Thinning and Harvesting--Reducing large accumulations of slash improves accessibility for tree planting and other silvicultural treatments; however, it may also increase seedling exposure to heat, drought and animal damage (Jemison and Lowden[11]). Harrison (1975) and Jemison and Lowden[12] found that partial burning of slash pieces may kill decay organisms outright and surface charring would impede the rate of natural decomposition of the material, impairing future access through the site for up to 50 years.

- To Reduce the Threat of Insect and Disease Build-ups in Slash Accumulations--Untreated slash may attract undesirable levels of dwarf mistletoe, tussock moths or pine bark beetles which can then damage residual trees, especially those weakened or previously injured.

  Hartesveldt et al. (1968)[13] referred to the sterilizing effect of fire in soil infested with pathogenic fungi. However, Jemison and Lowden[14] point out that the pathogenic fungus Rhizini undulata is stimulated by fire in some Pacific Northwest forests.

- To Expose Mineral Soil for Reforestation Site Preparation--The removal of surface duff and litter allows seed germination and seedling establishment in mineral soil; however, intense burns may damage soil productivity, inhibiting[15] seedling establishment and reducing growth potential (see Environmental Effects - Soil).

---

[9] From USDA FS PNW 1973, Slash Disposal Information Sheet.

[10] Contained in Cramer 1974.

[11] Ibid.

[12] Ibid.

[13] As cited in Dodge 1972.

[14] Contained in Cramer 1974.

West side--

Silvicultural burning on the West Side is used as a site preparation tool on clearcut logging sites and nonproductive brush lands. However, management objectives, budget constraints, weather problems and environmental concerns limit the application of fire to less than 25 to 40 percent of the total area treated each year depending on ownership.[16]

Prescribed understory burning is presently used on a limited basis on the West Side, but may increase in applicability as more "second growth" Douglas-fir stands are intensively managed.[17]

"Old growth" Douglas-fir stands on the West Side may accumulate up to several feet of litter and duff under natural conditions. Clearcut logging activities in these stands may generate as much as 200 tons of slash per acre (Dell and Ward 1972). Although no data are presently available to indicate the impact of slash accumulations on total stocking in the Pacific Northwest, field interviews indicate that slash-caused seedling mortality and site unplantability will commonly reduce stocking to 50 percent of the normally expected level.[18]

Prescribed burning after logging can reduce slash obstacles and expose mineral soils as is necessary to establish new tree seedlings (Martin 1974). This may be especially true for Douglas-fir, a species with serotinous cones which regenerate best on fire-prepared seedbeds in the open. In a 1973 study by Vyse and Muraro, broadcast burning reduced heavy logging slash and increased planting site suitability for reforestation efforts. In the study area of Vancouver Island, British Columbia, pretreatment slash loads ranged from 120 to 180 tons per acre. In this condition, 14 percent of the area was rated as plantable with little or no difficulty. Broadcast burning reduced slash loads to a level such that 100 percent of the area was rated plantable and the cost of of planting was decreased.

In an earlier study, Morris 1970 observed 58 pairs of clearcut plots in the Cascade and Coast Ranges of Oregon which were either burned or left untreated. He concluded that burning consumed nearly all material up to 11 inches in diameter and reduced litter beds and rotten wood.

---

[15] Contained in Cramer 1974.

[16] Personal communication, A. Hedin, Washington Department of Natural Resources; S. Wells, Oregon Department of Forestry.

[17] Personal communication, F. Graf, Oregon Department of Forestry.

[18] Personal communication, F. Graf, Oregon Department of Forestry; A. Hedin, Washington Department of Natural Resources.

In field observations of several slash treatment study units on the Wind River Experiment Forest - Gifford Pinchot National Forest, mechanical piling of old growth Douglas-fir logging residue to a residual slash load of 15 tons per acre was sufficient to allow access for tree planting, but did not reduce the 1 to 3 foot accumulations of duff and litter. Broadcast burning of similarly logged areas on the Gifford Pinchot did however reduce duff and litter accumulations and expose the mineral soils.[19]

A 1977 survey in Oregon established that 30 percent of the 3.8 million forested acres in the coast range is underproductive, although the area contains 70 to 75 percent of the State's best growing sites for commerical Douglas-fir stands (Oregon State 1977). Seral communities of alder and associated brush species, especially salmonberry, thimbleberry and vine maple now occupy Douglas-fir sites which were logged or otherwise disturbed but not replanted with Douglas-fir. Washington has a similar problem.

Silvicultural burning is used as a site preparation tool for converting these immature alder stands and brushlands to the more desirable stands of Douglas-fir. An effective burn treatment may remove planting obstacles and inhibit brush competition and eliminate the need for follow-up treatments as is required when mechanical or herbicide treatments are used.[20]

In field applications, Publishers Time Mirror, Inc. found that prescribed burning of brush prior to planting controlled competing brush species for up to 5 years with no further brush treatment. However, in areas in which non-burning mechanical or chemical treatments were used, follow-up chemical treatments were necessary within 2 to 3 years.[21] D. Robinson, Associate Professor, Oregon State University, supported these findings in his testimony before the ITF-FSU (September 13, 1977) in which he stated that burning will retard brush growth for 2 to 5 years, allowing planted tree seedlings to become established without additional treatments. However, Roberts (1975) found that some shrub species resprout rapidly after a brown and burn treatment and could necessitate follow-up application of selective herbicides.

Animal damage to established seedlings may also be reduced by temporarily eliminating animal habitats with fire. Studies by Hooven (1973, 1976) show that prescribed fires may reduce small animal populations by as much as 50 percent by eliminating protective cover vegetation.

---

[19] Personal communication and field observations with N. Paulson, USDA FS, October 7, 1977.

[20] Personal communication, C. Lingler, USDA FS Sinslaw National Forest, November 11, 1977.

[21] Personal communication, E. Feddern, Publishers Time Mirror, Inc., October 11, 1977.

Mountain beaver (Aplodontin rufa) have been observed to clip up to 100 percent of untreated plantations within a few weeks of planting. The application of burning prior to planting in conjunction with post-plant trapping has been shown to reduce mountain beaver damage to an insignificant level.[22]

East side--

Silvicultural burning on the East Side, in the form of periodic prescribed understory burning, is used to enhance site conditions for seedling establishment and to maintain open stand stocking to avoid growth stagnating competition (Hall 1977).

Roe and Beaufait (1971) reported that the initial growth of ponderosa pine seedlings may be as much as 50 percent greater on burned seedbeds as compared to other nonburn seedbed treatments.

Weaver (1947)[23] found that the growth rate of ponderosa pine is greatly increased in fire-thinned stands as compared to unthinned stands. In another study, Weaver[24] also suggested that fire exclusion in ponderosa pine may lead to greatly increased competition, weakening the trees and making them more vulnerable to insect attack. Studies by Hall (1977) support Weaver's earlier findings and indicate that the exclusion of fire or other thinning tools may result in growth stagnation of ponderosa pine thickets. Instead of a classical stand development in which dominant trees eventually eliminate suppressed trees, stagnation over a period of 50 to 100 years may limit diameter growth to 1 inch per 50 to 75 years and height growth to 4 to 6 inches per year.

Hall (1977) also found that fire may enhance the growth of ponderosa pine by volatilizing growth inhibiting pine-specific allelopathic substances which are suspected to accumulate in pine litter and associated soils. On several sites where fire had been excluded and accumulations of litter were present, the growth of ponderosa pine was significantly reduced while the growth of nearby white and Douglas-fir appeared normal.

Prescribed burning has also been shown to effectively control competing hardwoods underneath an established pine stand (Brender and Cooper 1968). Experiments on the Hitchiti Experimental Forest near Macon, Georgia resulted in the following conclusions:

- Prescribed fire effectively reduced hardwood stems 2 inches dbh and smaller

---

[22] Personal communication, E. Feddem, Publishers Time Mirror, Inc., October 11, 1977.

[23] As cited in Dodge 1972.

[24] Ibid.

- Repeated burns were necessary to control sprout growth
- Pine reproduction became established on burned-over areas
- Sufficient litter remained unburned on 10-20 percent of the slopes to protect against soil erosion.

The present use of fire on the East Side may also help to control insect infestation. Martin et al. (1976) mentions research underway to determine if Douglas-fir tussock moth damage can be reduced by introducing periodic fire to prevent the ingrowth of susceptible Douglas and true fir on sites more suitable to pine.[25] He also indicates that the severity of mountain pine beetle (Dendroctonus monticola) infestations may also be reduced by periodic burning to control tree spacing.

Wildlife and Range

Prescribed burning may be used to improve wildlife habitats and enhance range conditions (Stoddard 1931, Mobley 1973). However, prescribed burning objectives in the timber-producing areas of the Pacific Northwest may preclude optimum prescriptions for wildlife or range. Mobley et al. (1973) indicated that the size and frequency of a burn for timber management will not always enhance the requirements of wildlife and range. It may be that wildlife and range considerations are not a primary reason for burning in these areas as are hazard reduction and silvicultural improvement, but rather are merely expected spin-off benefits.

Periodic prescribed burning will maintain important wildlife forage and browse vegetation in areas where woody shrubs and trees would normally invade. However, recent studies in the Pacific Northwest by Hooven (1973, 1976) indicate that the wildlife benefits from burning are generally no different than those derived from clear cutting, although specific vegetative types and associated animal species will be affected differently (see OTHER ENVIRONMENTAL EFFECTS: Wildlife).

Prescribed burning may also enhance range conditions in East Side ponderosa pine-type forests. Mobley (1973) indicated that grazing conditions may be improved by fire in the following ways:

- Increased forage production
- Increased forage palatability
- Increased forage availability

---

[25] Douglas-fir Tussock Moth Program, USDA FS Bend Silviculture Laboratory and the University of Washington.

- Increased forage quality
- Removal of dead material
- Reduction of competing vegetation.

Pearson et al. (1972)[26] studied the effects of prescribed burning on forage plants in a ponderosa pine-bunchgrass vegetative type. One year after burning, the digestibility of forage plants increased and nitrogen and phosphorus contents were higher. However, Stoddard et al. (1975) indicated that repeated burning and overgrazing of perennial bunchgrasses may perpetuate inferior subclimax stands of annual bromegrasses.

It is, however, evident that prescribed burning in ponderosa pine-bunchgrass communities does increase forage production by reducing overstory competition from trees and brush (Pearson 1967). Studies by Hall (1977) in the Blue Mountains of Oregon concluded that crown cover in areas of fire exclusion increased from a normal coverage of 50 percent to about 80 percent. The associated forage production was reduced from 500-600 pounds per acre to as little as 50 to 100 pounds per acre.

USDA Forest Service estimates indicate that of the 2,118,000 acres of ponderosa pine forests on the East Side which may be suitable[27] for grazing, 45 percent may be unavailable because of dense brush or trees.[28]

BURNING TECHNIQUES

The season and hour-of-day of a proposed burn treatment will affect the fire behavior expected from a particular prescribed burning technique. Generally, when fuel is dry enough to burn efficiently, the hazard of wildfire is great and when meteorological conditions are most suitable, fuels may not burn efficiently (Harrison 1975). Preferred burning conditions will vary with management objectives, but are generally within the following ranges (Cooper 1975):

Fuel moisture content - 6-15 percent

Relative humidity - 30-50 percent[29]

Wind speed - 2-10 mph.

---

[26] As cited in Stoddard et al. 1975, p. 438.

[27] Less than 30 percent slope.

[28] Personal communication, L. Volland, USDA FS, December 2, 1977.

[29] Personal communication, R. Johansen, January 30, 1978.

In the Pacific Northwest, meteorological conditions and smoke management requirements limit the number of available days with optimal burning conditions. These constraints have necessarily required burning during the less than optimal periods of high fire hazard or high fuel moisture.

Ignition devices currently utilized with varying success in the Pacific Northwest and in other regions of the country are listed with their respective advantages and disadvantages in Table 1.

Prescribed burning techniques employed in the Pacific Northwest may be divided into three general categories: broadcast burning, pile burning and understory burning. The successful application of each may vary depending upon prevailing meteorological conditions, fuels and topography.

Broadcast Burning

Broadcast burning is an "in place" method of logging slash disposal and brushland conversion. The size of the area burned and ignition devices and technique used depend upon the particular environmental conditions and treatment objectives on each site.

There are four basic ignition patterns commonly utilized for broadcast burning: (1) strip, (2) ring, (3) center, and (4) area. Each pattern may be influenced differently by local atmospheric conditions affecting the fire behavior and resulting emissions (Beaufait 1966).

Strip Ignition--

Backing fires are set along the downwind side of the intended burn area and allowed to "back" into the wind. Field studies indicate that total fuel consumption by backfires consumed more litter fuel and less vegetative fuel than do head fires (Hough 1968).

Head fires are set along the windward side of the intended burn area and allowed to run with the wind. This type of fire front is typically fast moving.

Strip head fires are parallel head fires set across the intended burn area progressively from the downwind side toward the windward side. Flare-ups may occur when fires meet.

Flank fires are set in strips parallel to the wind and allowed to spread at an angle to the wind.

Ring Ignition--

Ring ignition is accomplished by firing the perimeter of the intended burn area and allowing the fire to burn towards the center. This type of ignition pattern is typically used in gentle terrain and light fuels.

TABLE 1. PRESCRIBED BURNING IGNITION DEVICES

Ignition Device	Type of Burn	Advantages	Disadvantages	Reference
Matches	Understory	Always available in quantity Rapidly dispensed	Require fine, dry fuels Localized ignition Poor in wind	Beaufait 1966
Fusees	Broadcast, Pile	Light in weight, convenient May be extended on pole Hot, concentrated flame Relatively long-burning May be thrown	Require fine fuels Localized ignition No residual flame	Beaufait 1966
Propane torches (backpack)	Broadcast, Understory	Very hot flame Long burning Maintain own pressure Good for piled slash	Heavey and awkward Time-consuming refill Refill can be hazardous No residual flame	Beaufait 1966
Diesel flame-throwers (truck-mount)	Broadcast	Long residual flame Long burning Fast roadside ignition Wide ignition pattern	Restricted to near roads Require gasoline pump Require large quantities of fuel	Beaufait 1966
Diesel flame-throwers (backpack)	Broadcast, Understory	Residual flame Easy refill	Heavy and awkward Require pressurizing	Beaufait 1966
Hand drip torches	Broadcast, Pile, Understory	Residual flame Light and portable Fast igniting	Need frequent refills Awkward in heavy slash	Beaufait 1966
Very flares and thermite grenades	Broadcast, Pile	Some residual flame Remote ignition possible	Relatively costly May burn too hot for slash ignition	Beaufait 1966
Jelled petroleum (Napalm) in sausage casings or cannisters	Broadcast, Pile	May be ignited with fuse or electrically Good for piled slash Persistent flame May be preset days ahead	Require presetting Requires constant surveillance Time-consuming to layout	Schimke & Dell 1969 Beaufait 1966
Heli torch	Broadcast	Remote ignition Rapid dispensing Good for inaccessible slash Residual flame	Poor in hardwood in marginal weather	Hedin 1977
Napalm grenade	Broadcast	Forty sec pull fuse Hand thrown remote ignition Persistent flame	Poor in hardwood	Dell & Ward 1967

Center or Internal Ignition--

Center or internal ignition is accomplished by igniting the center of the burn block and allowing the fire to burn towards the perimeter.

Area Ignition--

Area ignition is accomplished by checkerboard firing or spot ignition of the burn block and allowing each spot to burn into another.

One or more of the following mechanical or chemical pretreatments may be used in combination with broadcast burning.

Slash and Burn--

Unmerchantable logs, saplings and brush remaining after a clearcut logging operation or present on a potential timber-growing site may be mechanically or hand-cut (slashed) and then broadcast burned.

Mechanical "Hydro-axe" and "Tomahawk" slashers operate efficiently in relatively small slash, but are restricted to areas accessible by tractor. Observations on the Deschutes National Forest indicate that Tomahawk treatment without follow-up burning does not substantially reduce wildfire hazard[30] (Section 5 - ALTERNATIVES TO BURNING). A 2- to 3-month interim period between slashing and burning may be required to allow enough desiccation and compaction of fuels for an efficient burn treatment.[31]

Brown and Burn--

Green slash and brush areas may be more efficiently burned if treated with chemical herbicides or desiccants 2 weeks[32] to 12 months[33] prior to broadcast burning. The herbicides and desiccants used and application rates are shown in Table 2.

Field applications by the Washington Department of Natural Resources demonstrated that the application of the contact herbicide Dinitro followed by mass ignition broadcast burning produces satisfactory fire behavior in situations where conventional torch ignition would be ineffective (Hurley and Taylor 1974). Mass ignition utilizes helitorch or napalm ignition devices discussed previously in Table 1. Entire burn blocks may be enveloped within minutes with high fire intensity characteristics.[34]

---

[30] Personal communication, W. Shenk, USDA FS PNW, November 11, 1977.

[31] Personal communication, E. Feddern, Publishers Time Mirror, Inc., October 11, 1977.

[32] Hurley and Taylor 1974.

[33] Personal communication, E. Feddern, Publishers Time Mirror, Inc., October 11, 1977.

[34] Personal communication, A. Hedin, Washington Department of Natural Resources, October 5, 1977.

TABLE 2. BROWN AND BURN HERBICIDES AND DESICCANTS

Name	Chemical Structure	Application Rate*
Tordon 101	4-Amino 3, 5, 6 - Trichloropicolinic acid	1/4-8 lb/Ac
2,4,D	2,4 Dichlorophenoxy acetic acid	1/4-4 lb/Ac
2,4,5,T	2,4,5 Trichlorophenoxy acetic acid	1-4 lb/Ac
Round-up	N (Phosphonomethyl) glycine	N/A
Paraquat	1,1' Dimethyl-4,4' Bipyridinium methane sulfanate	1/2 lb/Ac
Dinitro	2 Sec Butyl 4,6 Dinitro phenol	1-12 lbs/Ac

* Thomson, W. T. 1977, Agricultural Chemicals Book 2: Herbicides

In a study by Roberts (1975), brown and burn treatment of brushfields in western Oregon prior to reforestation efforts was shown to greatly enhance the potential of planted conifers to assume dominance. The competing overstory of red alder was completely removed and other hardwoods and tall shrubs reduced. The author did however point out that shrub resprouting was rapid and could provide significant site competition necessitating follow-up applications of selective herbicides.

Pile and Burn--

Pretreatment of larger typically "unavailable" fuels by PUM or YUM techniques may increase the efficiency of broadcast burning (Dell 1977). The remaining small dimensional fuels would produce a low intensity burn with less smoldering material, thus reducing the residual burn-out time or smoldering stage.

Pile Burning

Pile burning of slash is accomplished by PUM or YUM techniques to concentrate material into piles or windrows.

PUM is accomplished by tractor or hand. Tractor piling is limited to slopes less than 30 to 35 percent where soils will not be adversely affected by tractor compaction. In areas accessible to tractors, continual bunching of the material as the burn progresses increases the fire intensity and material consumption (Harrison 1975). Tractor movement may also scarify the site, exposing mineral soil for favorable regeneration planting sites (Beaufait 1966). However, the use of tractors may also decrease burning efficiency and increase the chance of residual smoldering by mixing soil and rock with the slash to be burned. Harrison (1975) points out that this problem may be eliminated by the use of a "rock rake" instead of a dozer blade attachment.

Windrow piling utilizes crawler and ignition crews more efficiently than standard PUM techniques (Beaufait 1966). Vertical windrowing may reduce soil erosion by directing tractor scraping across the slope and allow for more efficient fire control when the windrows are burned from either the bottom or top of the slope. Field applications by Boise-Cascade (Elmgren 1977) show that tractor windrow piling and burning using a helicopter drip torch is a cost-effective means of disposing of logging slash to allow for reforestation.

YUM is accomplished by "high-lead" or other cable logging machinery on slopes inaccessible to tractors. Slash material is pulled to the log landing or road, concentrated in piles and later burned.

Present Forest Service timber sale contracts in the Pacific Northwest may contain YUM or PUM provisions, requiring that loggers yard or pile all slash over 5 to 8 inches in diameter (Harrison 1975). This facilitates pile burning or exportation for utilization (see Section 5 - ALTERNATIVES TO BURNING). Hall (1967) found that piling or windrowing of slash before burning substantially increases the percentge of total material and pieces larger than 4 inches in diameter that will be consumed. However, Burwell (1977b) indicated that the extreme fire intensity of pile burning may also sterilize the soil beneath the pile site (see OTHER ENVIRONMENTAL EFFECTS: Soil).

Pile burning may be utilized when insufficient fuel is available to support a broadcast burn or when burning must be done during wet or snowy periods (Beaufait 1966). An ignition spot can be kept dry using a covering of paper, tar paper or plastic. Favorable meteorological conditions for smoke dispersion during the winter months increases the desirability of deferred pile burning. Pile burning may also be utilized during the summer wildfire season when extreme fuel and meteorological conditions would normally preclude broadcast burning. Cooper (1975) indicated that pile burning may reduce the risk of fire escape by eliminating the need for predictable directional winds as are desired when broadcast burning.

Material combustion by pile burning or broadcast burning may result in air pollution due to incomplete combustion. Unburned emissions escape when temperatures above the fire decrease to levels insufficient for complete combustion as shown in Figure 6.

Portable fans may be used to increase the combustion of pile-burned material by supplying oxygen and a measured amount of fuel oil although Harrison (1975) observed that combustion efficiency is only "marginally" improved.

Understory Burning

Understory burning can be used in forested areas to efficiently reduce undesirable light fuel loads without damaging desirable residual vegetation. Strip ignition patterns as described on page 29 are typically utilized for understory burning.

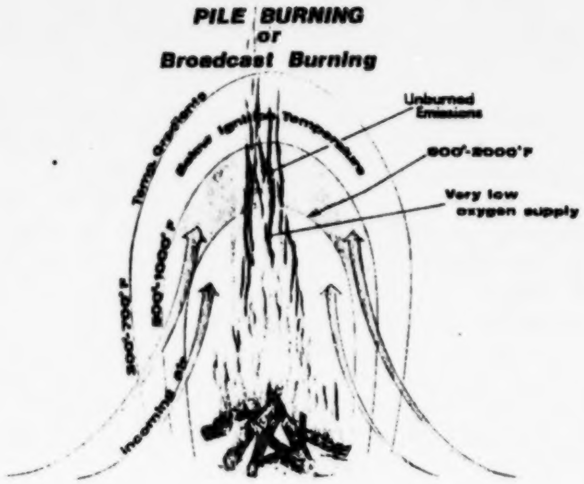

PILE BURNING
or
Broadcast Burning
Temp. Gradients
Below Ignition Temperature
Unburned Emissions
800°-2000°F
Very low oxygen supply
800°-1000°F
500°-700°F
Incoming air

Figure 6. Incomplete combustion temperature profile of pile or broadcast burn. (Harrison 1975).

Schimke and Green (1970) indicated that a controlled flame height of 2 feet or less would efficiently consume litter and duff fuels and reduce brush and other undesirable vegetation. Martin[35] indicated, however, that a flame height of 5 feet may be used to give a 20-foot scorch height for pruning or reducing mistletoe infestation. The application of a particular ignition device and pattern may not always produce a fire intensity and rate of spread that will meet these objectives.

Burning heavy accumulations of thinning or partial-cutting slash which may cause unacceptable fire damage to residual trees can be left to decompose for 4 to 6 years before burning (Dieterich 1976). This untreated thinning slash may be regarded as a high wildfire hazard and require "extra protection" until treated or sufficiently decomposed (see Section 5 - ALTERNATIVES TO BURNING).

---

[35] Personal communication, R.E. Martin, USDA FS, July 18, 1978.

PRESCRIBED FIRE IN FOREST MANAGEMENT - OVERVIEW

This report has thus far introduced prescribed burning in the context of forest management applications, the reasons for burning and the burning techniques utilized. Prescribed burning has been shown to be a useful management tool when the fire can accomplish silvicultural objectives without adversely affecting other environmental resources. However, the absence of comprehensive guidelines for the use of prescribed fire in the Pacific Northwest may evidence the difficult task of developing prescriptions for all environmental conditions and management objectives. It may also attest to the notion that "...prescribed burning is still more of an art than a science."

This section is an overview of the economic and other environmental impacts of prescribed burning. They would not normally be addressed in a study of the impact of forestry burning upon air quality, but may be of importance for a clear and total understanding of the overall implications of prescribed burning and the trade-offs which must be considered in its use, or the use of a nonburning alternative technique.

Economic Impacts

Section 317(a)(4) of the Clean Air Act Amendments of 1977 requires that any action taken by the EPA Administrator which would be used to prevent deterioration of air quality must be preceeded by an Economic Impact Assessment. The requirements of this act are quite similar to the information needed to provide an economic assessment of the impacts of forest burning upon air quality along with the potential for alternate management techniques.

A discussion of the economics of forestry burning and nonburning alternatives are presented in Section 5.

Other Environmental Impacts

The impact of prescribed burning on other forest resources is briefly discussed in this section to provide background information necessary to fully understand the potential environmental impacts from alternative nonburning techniques as discussed in Section 5 (see Section 5 - ALTERNATIVES TO BURNING). In general, although the immediate impact of fire is often intense and dramatic, long-term effects are usually buffered by the natural regenerative ability of forests. In many instances fire is recognized as a natural component of forest ecosystems, guiding the successional progress of plant and animal communities. Douglas-fir forests throughout the Pacific Northwest are an intermediate sere resulting from catastrophic fire disturbances. They exemplify the natural role that fire has played in the characterization of this region.

Water--

Prescribed burning may indirectly affect the quality of surface water if riparian vegetation is reduced. Mobley (1973) observed that a reduction in vegetative cover will increase surface runoff. The resulting erosion may wash mineral soils and nutrients into adjacent streams, increasing the turbidity and altering the chemical content of the water. Snyder (1975) measured increased levels of pH, electrical conductivity, nitrate, bicarbonate, sulfate, potassium, calcium and magnesium in streams adjacent to burned areas. Organic nitrogen may constitute up to 53 percent of the nutrient increases (Fredriksen 1971). Water temperature has increased by as much as 11.4°C (Levno and Rothacher 1974).[36] However, these effects are expected to be temporary, diminishing as the riparian vegetation becomes reestablished.

Fire intensity, and the associated consumption of surface duff and litter, affects soil erodibility (Dyrness and Youngberg 1957). Light burning may partially consume duff and litter accumulations, but does not affect physical soil properties. Severe burning may consume all litter and duff and expose mineral soils to erosion. Soil erodibility will vary with slope and soil type. However, there are several factors that can minimize the impact of severe burning on soil erodibility:

- Severely burned areas are not usually found on steep slopes which are normally most susceptible to erosion.
- Severely burned areas are usually small and scattered.
- Fire may form a protective crust on some soil types.

The effects of prescribed burning on water quality may be minimized by leaving a forested buffer strip between burn areas and adjacent streams (USDA FS 1973).

Vegetation--

Prescribed burning can significantly alter the vegetative composition or perpetuate a successional stage of a forest. Studies in the Pacific Northwest by Habeck et al. (1973) and Hall (1974) show that periodic fires may reduce the incursion of competing tree species into dominant forest stands. Fire may also facilitate tree regeneration by freeing serotinous cone seeds, exposing mineral soil seed beds and releasing soil minerals and nutrients (Roe 1971, Heinselman 1970).

Several factors contribute to the degree of vegetative tolerance to fire. The immediate lethal effect of fire is due to combustion and heat.

---

[36] As cited in Cramer 1974.

Temperatures above 55 to 60°C may result in cell death. However, the temperature required to kill vegetative tissue is inversely related to the time of exposure. Douglas-fir phloem, cambium and foliage which can withstand a temperature of 49°C for 1 hour will succumb to a temperature of 60°C within 1 minute (Martin 1977).

Tree species exhibit varying degrees of tolerance to fire. Mature ponderosa pine, Douglas-fir and larch are considered to be extremely fire resistant because of their characteristically thick bark, buds and stems, although young saplings of these species are relatively sensitive to fire. Fire-sensitive species include lodgepole pine, western white pine, true fir, Engelmann spruce, and quaking aspen. However, Roe (1971) observed that the fire tolerance of tree species may depend on site conditions as reflected by the successional position of the species.

Issac (1943) reported that fire will inhibit or eliminate many shrub species including salal, oregon grapes, vine maple, and salmonberry. However, many shrub species that are totally consumed by fire above ground will sprout prolifically from root crowns. Fire may also enhance the regeneration of shrubs with heat-germinated seeds (Haebeck and Mutch 1975).

Vogl (1969), Hooven and Black (1976), Lyon (1972) and others reported that the density and diversity of herbaceous and grass species increase after burning.

Wildlife--

Hooven (1973), Reeves (1973), and the University of California (1971) stated that prescribed burning benefits large animals by increasing browse palatability and accessibility. Swanson (1970) and Harper (1971) have documented the improved habitat for large game following prescribed burning in Douglas-fir stands of western Oregon.[37] Komarek found that following a burn, resprouting shrubs and herbaceous species contain high nutrient levels of protein, calcium, potash, and phosphorus.[38] Brown and Krygier (1967) reported that browse reaches optimum conditions for Roosevelt elk 7 years after logging and for deer 15 to 20 years after logging.[39] Hall (1971) reported that the exclusion of understory burnings has a long-term detrimental effect on wildlife by reducing cover and forage. Three shrub species contribute browse in dense fir stands while eight contribute in open park-line ponderosa pine stands.

The altering of the habitat by prescribed burning may have varied effects on other mammals. Hooven (1969), Tevis (1956a) and Moore (1940) found that deer populations return rapidly following a broadcast burn.[40] Koehler found that pine marten populations decreased immediately after a fire but in the long-run the new habitat supported more martens.[41] Hooven and Black (1976) found a smaller shrew population on a slash-burned Douglas-fir clearcut than on the adjacent mature stand due to a decreased insect population on the burned plot. However, field mice were found to be more prevalent on the burned area.

---

[37] As cited in Cramer 1974.

[38] As cited in Hooven 1973.

[39] Ibid.

Observations indicate that prescribed burning has little adverse effect on bird populations (USDA FS 1973). Fire may indirectly benefit bird populations by enhancing the growth of protective shrub cover and exposing seeds and insects. Stoddard (1931, 1962) showed that fire exclusion was responsible for a decline in quail populations in the Southeastern United States. In the Pacific Northwest many birds, including quail, are attracted to clearcut areas that have been burned (Hooven 1973).

Wilderness and Aesthetics--

Increasing public interest in "pristine" wilderness areas has identified a need for a better understanding of the natural role of fire in forests. Fire is a most common natural disturbance that will shape a forest stand and characterize the forest community (Smith 1962). The visually pleasing open park-like stands of ponderosa pine forests have been perpetuated by periodic understory burning and the habitat of many wild animals and desirable vegetative species have been enhanced by fire treatments.

There are no definitive studies in the Pacific Northwest showing how people react to specific prescribed burning treatments. However, Williams (1975) indicates that, in general, public reaction to burning will be emotional and negative.

The visual impacts of prescribed burning may elicit the most reaction. Harrison (1975) observed that the large partially burned pieces of slash and cull logs that remain after burning give an appearance of vast waste, although actual destruction is much less than would be expected from a catastrophic wildfire. Also, the smoke from forestry burning may be displeasing in rural areas which are not commonly associated with atmospheric pollutants, although Hough and Turner (1972)[42] found that there is not a direct correlation between visible smoke and the amount of burning activity.

Public sentiment against burning, if any, may in part be attributed to the success of the USFS "Smokey the Bear" campaign coupled with a lack of understanding of the reasons for prescribed burning and a lack of scientific knowledge of potentially detrimental environmental impacts.

---

[40] As cited in Cramer 1974.

[41] As cited in Moore 1976.

[42] As cited in Williams 1975.

Soils--

Hall (1977), Stone (1971) and Wells (1971) all point out a basic factor that must be kept in mind when assessing the effects of fire on soil. There are short-term influences that alter the productivity (both for good and bad), but the soil system tends to buffer these effects and fairly rapidly return to an equilibrium not too different than that seen before the burn. These soils developed under conditions of periodic burning by either wildfires or those set by the aboriginal populations.

Dyrness and Youngberg (1957a, b), Tarrant (1956a, b), and Ralston and Hatchell (1971) have all evaluated the effects of fire on soil physical properties and have all concluded that there is essentially no significant effect unless the fire is severe. This occurs in less than 10 percent of the area during broadcast burns. These severe burns occur under piles of slash that often accumulate in the bottoms of draws and on log landings.

This effect could present a problem for PUM and YUM operations where 5 percent of an area's soils may be sterilized by the severe burns under piles. By judicious placement of piles, the effects can be minimized.

Any disturbance to the soil is likely to alter erosional patterns, however, Ralston and Hatchell (1971) note that these factors are ameliorated with the invasion of shrubs and forbs into the area following the burn. Dyrness and Youngberg (1957a, b) point out that on the lightly burned areas erosion should not be markedly different from the unlogged areas; however, more research needs to be done in this area and Ralston and Hatchell (1971) voice this same conclusion.

Nutrient regimes are definitely altered by fire. Some factors are beneficial, others detrimental. The work by Grier and Cole (1971) at the University of Washington indicate a definite release of nutrients to the soil, but notes that these are rapidly adsorbed onto the soil colloids. A more striking finding was reported by Wells (1971). The loss of nitrogen (N) from the litter was offset by the same rate in accumulation in the 0-2" layer of mineral soil. Wells (1971) reports that the increased burning leads to a stimulation of nonsymbiotic fixation of N. Stone (1971) speculates that this is most likely brought about by blue-green algae, which have been shown by Jurgensen and Davey (1968) to be present in acid forest soils and are known to be stimulated by increased pH which could result from the released nutrients after a burn. This increase in N fixation along with the mineralization is believed to be the reason that there is little apparent loss of available N following a fire on some sites.

In comments on Wells' (1971) paper, Dr. William L. Pritchett of the University of Florida Soils Department, observes that fire is a rapid method of oxidizing the organic matter on the forest floor; the same action is carried out over longer time periods by microorganisms. Dr. Charles Davy of North Carolina State University makes a similar observation in conjunction with a paper by Jorgensen and Hodges (1971). Davy notes that the organic matter in the A_1 horizon of the soil is on the order of 300 to 800 years old. The material destroyed by fire is not this "old" material but the less resistant, readily oxidizable material. The key to the effects again depends upon the severity of the burn.

In summary, the consensus of opinion held by most forest soils specialists is that prescribed fires have relatively little effect on the soil system and that those effects that are seen are rapidly offset by the homeostatic tendencies of the ecosystem.

Political Setting

Any use of fire in wildland settings is an open invitation for controversy. Foresters themselves are often in disagreement over the use of prescribed fire.[43] Data have not been accumulated that enable a sound scientific evaluation to be made of the impact of fire on the ecosystem. Policy has been set based upon the emotions of the hour. Major conflagrations which originated in the early part of this century led to legislative mandates that said in effect: "There shall be no fires in the forest." The effort to educate the public to this goal through "Smokey the Bear" has been perhaps one of the best advertising schemes ever developed. In effect, it has been too successful.

The "no burn" philosophy of the first half of this century is slowly giving way to a more rational management goal, that of using fires as an effective management tool. This is reflected by the U.S. Forest Service Operations Manual,[44] where the following statement is made:

> "Protecting and managing forest and range environments for enhancement of productive potential in terms of wood, forage, water and recreation necessitates use of controlled burning."

The use of burning as a forest management tool is inevitably controversial. Not only does it run counter to the vision of fire as the enemy of forests and man which the Forest Service itself has so effectively engendered over many years, but it now appears to much of the public as a threat to environmental values about which the public had been little concerned as recently as 25 years ago. Among the new environmental values which controlled burning is seen to threaten are air quality, visibility, energy conservation, resource utilization and the ineffable values of what seems to the city-dweller's eye to be "wilderness" country.

---

[43] Smith, David M. The Practice of Silviculture, 7th ed., John Wiley & Sons, Inc., New York 1962.

[44] U.S. Forest Service Manual, Region 6, Supplement No. 62. February 1972. U.S. Department of Agriculture.

The new environmental consciousness has been enacted into environmental laws, among which the Federal Clean Air Act, particularly in its amendments of 1970, 1974 and 1977, provides mandates to the states to preserve the quality and appearance of their air in ways which are not readily compatible with the use of controlled burning in forest lands.

The stage has been set for controversy. On both sides the issues are expressed in terms of law, health, economics and available technologies, but there is a strong emotional underlay to the arguments. The advocates of environmental protection (in this case, the advocates of severe limitations on controlled burning) are defending a landscape as well as tangible values. Those responsible for implementing a policy of controlled burning as a forest management tool react emotionally, as well as logically, against a perceived threat to an industry, to an individual's job, or to an individual's ego. The employees of government agencies find themselves engaged in arguments on both sides of the issue, arguments which must be based in law and the marshalling of facts but which are difficult to disentangle from the emotional, and often political, background of the issues.

Early efforts toward meeting the requirements of the Clean Air Act and other air quality legislation were directed toward the more obvious sources of pollution. Slash fires were considered to be an "uncontrolled" source. Even though action to eliminate the use of fire was not instigated, efforts have been made to control the smoke emissions from the fires. Both Washington and Oregon have an active smoke management plan. These plans regulate the use of fire through the respective forestry organizations who are responsible for issuing burning permits. These programs have become increasingly effective as experience is gained in predicting smoke behavior under varying fuel, terrain and meteorological conditions.

The Federal and State agencies concerned with managing environmental quality and forestry production are increasingly aware of the interactions of their mandates and programs. Public awareness, still without a full understanding of all the issues involved, is also increasing in this area. Over the years the general public have not been overly tolerant of smoke. This attitude, along with the potential for health problems resulting from smoke inhalation, has created public reactions that are becoming more and more difficult to anticipate. Public pressures led the 1977 Oregon Legislature to take a serious look at the use of fire in grass seed production areas of the Willamette Valley. House Bill 2196 resulted. This bill states in Section 4:

> "468.455. [In a concerted effort by agricultural interests and the public to overcome problems of air pollution, it is the purpose of ORS 468.140, 468.150, 468.290 and 468.455 to 468.485 to provide incentives for development of alternatives to open field burning, to phase out open field burning and to develop feasible alternative methods of field sanitation and straw utilization and disposal.] In the interest of public health and welfare it is declared to be the public policy of the state to control, reduce

> and prevent air pollution caused by the practice of open field burning. Recognizing that limitation or ban of the practice at this time, without having found reasonable and economically feasible alternatives to the practice could seriously impair the public welfare, the Legislative Assembly declares it to be the public policy of the state to reduce air pollution by smoke management and to continue to seek and encourage by research and development reasonable and economically feasible alternatives to the practice of annual open field burning, all consistent with ORS 468.280."

Hearings and implementation of this legislation have revealed the nature of "prescribed" fire to generate political heat along with combustion products. The fact that slash fires occur at the same time the grass fields are burned was noted during the hearings on Oregon House Bill 2196. This raised the question as to the source of smoke in the Eugene-Springfield area. In an effort to further identify the impact of forest burning upon air quality, a Joint Interim Task Force on Forest Slash Utilization was set up by the Oregon State Legislature. This task force is attempting to determine a course of action for the State of Oregon in regard to reducing the air quality effects of prescribed burning. Foresters are quite concerned over the potential loss of the use of fire as a management tool.

The Federal Clean Air Amendments of 1977 passed by Congress in August 1977 place another potential restriction on the use of fire. These amendments contain three sections that have a potential effect in the Northwest. This act requires: (1) that significant deterioration of air quality will not be allowed in areas such as the designated wilderness areas; (2) preservation of visibility in Federal Class I areas by alleviating significant impairments; (3) initiation of a report to Congress on the effects of fine particulates on health and welfare.

The first requirement, which is the part of the 1977 Clean Air Act Amendements preventing significant deterioration of air quality, permits only minimal degradation of air quality within designated Class I areas. (The Class I areas include National Parks and wilderness areas.) At the present time, the smoke management plans in Oregon and Washington are designed to direct the smoke away from the designated areas lying in the Puget Trough and the Willamette Valley. Any requirement to direct smoke out of the Western Cascade area toward the east is likely to interact with the air in the National Parks and the wilderness areas lying along the Cascade Crest. If the Clean Air Amendments are interpreted so that they apply to these Class I areas, the smoke management programs will be greatly handicapped and prescribed forest burning further restricted. (This is discussed further in Section 6.)

The second requirement seeks to protect the scenic value of Class I areas from visibility impairment both now and in the future. This requirement is similar in its impact to that discussed above--smoke management will be greatly handicapped and thus more difficult to attain. The third requirement listed above is still open because of the lack of information. However, if research leads to special air quality standards for fine particulate matter, forestry burning may be greatly curtailed since the majority of the particulate matter emitted by forest burning is in the fine particulate range. The effect of forest burning upon fine particulate levels is further discussed in Sections 3 and 6.

This brief outline points up the dilemma of the environmental managers within the various governmental and private organizations. The public is demanding cleaner air at the same time the demands for inexpensive forest products are being made. An industry that is often marginal is being pressed to absorb additional costs or else risk an elevated probability of destructive wildfires. Legislative deadlines put pressure on pollution control agencies to act with limited knowledge to control pollution. Many environmental action groups want clear visibility, on one hand, and, on the other hand, do not want wildfire destroying the natural beauty. These are all conflicting points of view that must be addressed with no present mechanism for handling them. A system of checks and balances must be developed that will enable the managers within the Government to balance as many of the factors as possible in coming up with a decision. Research and legislative action must be taken to assist this decision process by enabling the manager to use a scientific basis for decisions rather than with emotion or legislative fiat alone.

SECTION 2

FORESTRY BURNING IN WASHINGTON AND OREGON

The locations and extent of forestry burning in Washington and Oregon are presented in this section through a series of maps and tables. Information on who is conducting burning activity, the type of fuel burned, burning techniques used, and relation to timber harvest activity is also presented.

LOCATION OF FORESTRY BURNING

Data on forestry burning activity were drawn from the Smoke Management Programs administered by the Washington Department of Natural Resources (DNR) and the Oregon Department of Forestry (DOF), and the Total Resources Information (TRI) System of the U.S. Forest Service (Region 6). Data for Oregon were drawn entirely from the Oregon Smoke Management System, a computerized system for recording planned and accomplished burns and operated as part of the Oregon Smoke Management Program. Data on burns conducted in Washington were drawn primarily from the Washington Smoke Management Plan annual reports or listings of individual burns provided by the DNR. Data on Federal burns conducted in Washington during 1975 and 1976 were drawn from the TRI System of the USDA FS.

The number of burns, acres burned, estimated tons of fuel burned and annual averages are summarized in Table 3 for the years 1975 through 1977. It should be emphasized that tons of fuel burned are estimates and subject to considerable error. This is especially true in the case of broadcast burning, where both fuel loading and percent of fuel consumed which are required to estimate fuel burned, are difficult to estimate reliably. Since tons of fuel burned are used in estimating pollutant emissions, the error in estimated fuel burned should be considered before drawing conclusions based on these figures. Attempts to determine the magnitude of the errors were unfruitful because of the lack of studies designed to provide estimates of the accuracy. A comparison was made between actual field sampling (reported by Dell and Ward 1971) and smoke management system data provided by the States of Washington and Oregon. Statistical tests on the data revealed considerable variablity in the tonnages burned per acre. The data often was consistent within a National Forest but varied considerably between National Forests. The data from the State of Washington was not different from the field measurements but the Oregon data revealed considerable differences. Most of the discrepancy between the field data and the Oregon Smoke Management estimates was due to high values reported for two National Forests.

The values reported in Table 3 may be reasonably accurate for the Washington areas but appear to be too high in Oregon. Some of the National Forest areas report values that averaged almost five times the

TABLE 3. SUMMARY OF FORESTRY BURNING ACTIVITY IN WASHINGTON AND OREGON, 1975-1977

County	1975			1976			1977			All Years (Average)		
	No. of Burns	Acres Burned	Estimated Tons of Fuel Burned	No. of Burns	Acres Burned	Estimated Tons of Fuel Burned	No. of Burns	Acres Burned	Estimated Tons of Fuel Burned	No. of Burns	Acres Burned	Estimated Tons of Fuel Burned
Washington:												
Clallam	82	3,424	65,354*	120	4,135	33,338*	87	2,945	95,940	96	3,501	64,877*
Clark	1	80	160*	6	430	8,450*	2	50	700	3	187	3,103*
Cowlitz	124	10,098	145,995*	116	9,237	262,493*	51	4,334	111,040	97	7,890	173,176*
Grays Harbor	74	4,685	79,865*	86	5,307	89,218*	74	5,372	104,930	78	5,121	91,338*
Island	0	0	0	0	0	0	0	0	0	0	0	0
Jefferson	59	2,612	84,094*	69	3,423	41,316*	86	3,467	80,460	71	3,167	68,623*
King	25	774	32,395*	33	1,228	48,507*	29	402	21,950	29	801	34,284
Kitsap	5	185	2,012	9	236	3,012	7	248	2,490	7	223	2,505
Lewis	129	4,331	41,040*	146	9,489	87,131*	240	8,572	301,230	171	7,464	143,134*
Mason	36	1,488	7,385*	90	4,101	15,670*	96	2,457	84,440	74	2,682	35,832*
Pacific	29	2,437	47,104	45	3,909	85,105	49	3,464	71,455	41	3,270	67,888
Pierce	21	1,044	25,610*	35	1,509	25,040	45	1,293	25,520	34	1,282	25,390
San Juan	0	0	0	0	0	0	0	0	0	0	0	0
Skagit	28	922	4,155*	55	1,443	12,270*	49	2,266	63,400	44	1,544	26,608*
Skamania	251	7,907	7,610*	199	11,588	39,990*	289	9,687	363,510	246	9,727	137,037*
Snohomish	49	1,387	25,140*	58	2,196	9,730*	39	1,541	45,120	49	1,708	26,663*
Thurston	25	1,123	23,202*	18	280	24,500*	11	410	5,440	18	604	17,714*
Wahkiakum	2	136	4,700	5	214	6,516	5	542	4,150	4	297	5,122
Whatcom	31	940	2,280*	36	1,005	15,555*	17	1,034	41,580	28	993	19,805*
Combined Western Counties	971	43,573	1,540,031†	1,126	59,730	1,869,281†	1,176	48,085	1,423,350	1,090	50,461	1,610,889†
Combined Eastern Counties	264‡	74,323§	1,495,374§	423	57,331§	1,788,150§	336#	53,228**	1,227,260**	374††	61,627‡‡	1,503,595‡‡
Statewide Totals	1,235‡	117,896§	3,035,405§	1,549	117,061§	3,657,431§	1,512#	101,313**	2,650,610**	1,432††	112,090‡‡	3,114,482††

(continued)

* Figure does not include burns by the U.S. Forest Service for 1975 and 1976.

† Figure includes fuel burned by the U.S. Forest Service in Western Washington, as reported in the Annual Summary of Prescribed Burning Activities conducted under the Washington Smoke Management Plan.

‡ Figure does not include burns conducted by the Bureau of Indian Affairs in Eastern Washington or the U.S. Forest Service in the Colville National Forest.

§ Figure does not include burns conducted by the U.S. Forest Service in the Colville National Forest.

# Figure does not include burns conducted by the Bureau of Indian Affairs in Eastern Washington and the U.S. Forest Service in the Colville and Umatilla National Forests.

** Figure does not include burns conducted by the U.S. Forest Service in Colville and Umatilla National Forests.

†† Figure does not include burns conducted by: the Bureau of Indian Affairs in Eastern Washington during 1975-77, the U.S. Forest Service in the Colville National Forest during 1975-77, and the U.S. Forest Service in the Umatilla National Forest during 1977.

‡‡ Figure does not include burns conducted by the U.S. Forest Service in the Colville National Forest during 1975-77 and the Umatilla National Forest during 1977.

NOTE: Tonnage figures may be high. See page 43 for discussion of possible error.

TABLE 3. (continued)

County	1975			1976			1977			All Years (Average)		
	No. of Burns	Acres Burned	Estimated Tons of Fuel Burned	No. of Burns	Acres Burned	Estimated Tons of Fuel Burned	No. of Burns	Acres Burned	Estimated Tons of Fuel Burned	No. of Burns	Acres Burned	Estimated Tons of Fuel Burned
Oregon:												
Benton	24	321	4,985	34	1,290	21,336	23	597	5,002	27	736	10,441
Clackamas	316	6,771	249,298	419	4,858	428,998	389	4,187	199,684	375	5,272	292,659
Clatsop	3	338	12,180	9	382	6,907	6	404	14,855	6	375	11,314
Columbia	8	366	12,875	18	578	17,903	8	495	4,748	11	480	11,842
Coos	127	3,409	129,986	197	5,306	172,664	159	5,582	137,725	161	4,766	146,792
Curry	77	1,927	83,199	137	4,573	143,407	117	2,987	141,753	110	3,162	122,786
Douglas	526	23,905	653,297	630	21,994	886,523	601	21,542	888,965	586	22,480	809,805
Hood River	57	2,364	29,205	86	2,149	59,385	56	740	45,472	66	1,751	44,687
Jackson	69	5,713	491,962	98	6,668	507,946	135	13,332	448,012	101	8,571	482,640
Josephine	74	1,089	104,365	87	1,639	116,674	75	2,122	132,551	79	1,617	117,863
Lane	604	18,421	756,431	878	25,874	1,288,766	626	22,791	761,692	704	22,362	935,629
Lincoln	66	1,820	40,937	109	4,161	155,506	100	5,037	98,021	92	3,673	98,155
Linn	158	3,123	114,020	312	10,858	279,515	277	8,769	261,745	249	7,583	218,426
Marion	36	821	26,628	57	1,076	40,434	104	2,732	96,367	66	1,543	54,476
Multnomah	49	251	51,627	35	419	61,530	38	511	44,713	41	394	52,623
Polk	8	135	4,250	14	550	16,475	17	676	12,409	13	454	11,045
Tillamook	54	1,851	72,261	85	2,897	95,896	40	1,745	42,470	59	2,164	70,209
Washington	2	94	1,966	3	59	1,904	3	134	3,915	3	96	2,595
Yamhill	11	219	7,125	25	606	28,843	23	589	21,845	20	471	19,271
Combined Western Counties	2,269	72,938	2,847,227	3,233	95,937	4,330,612	2,797	94,972	3,361,943	2,769	87,949	3,513,258
Combined Eastern Counties	103	5,593	131,222	93	1,923	157,283	214	3,395	192,592	137	3,637	160,366
Statewide Totals	2,372	78,531	2,978,448	3,326	97,860	4,487,895	3,011	98,367	3,554,535	2,904	91,586	3,673,624

average for the field measurements derived from the data reported by Dell and Ward (1971).

Examination of the data gives a clue to the likely problem. Many of the areas appear to be reporting total fuel loading rather than tons of fuel burned. (Better supervision and data quality control should greatly reduce much of the discrepancy.) Dell and Ward reported that the fines (< 3") averaged from 20-40 tons per acre. Most fuels management personnel consider that this is a reasonable figure and closely follows the tonnages burned in slash fires. In some cases values as high as 350 tons per acre were reported. These high values more closely follow total tons of fuel on the ground than tons consumed by the fire.

Until a field check is undertaken, these estimates cannot be considered as more than indications of the amounts of material burned. Fuels management specialists are attempting to refine the basis for estimating the amount of materials burned in order to develop more reliable figures. Future estimates should improve greatly as a result of these new techniques. Better data management will also help improve the quality and reliability of the estimates made.

Table 3 contains fuel tonnages for each county on the West Sides of the two states and summaries of East Side, West Side, and state totals. Washington counties which are missing data on "Estimated Tons of Fuel Burned" for USDA-FS area burns are flagged with asterisks (*). West Side summary figures for "Tons of Fuel Burned" do include USDA FS burns.[1] Tonnages reported for "Combined Western Counties" are thought to be complete. East Side figures for Washington are footnoted to indicate missing data. The number of burns on the East Side does not include burns conducted by the Bureau of Indian Affairs (BIA). However, acres and estimated fuel burned do include data for BIA burns. East Side figures also do not include burns conducted by the USDA FS in the Colville National Forest for the entire period 1975-1977 and for the Umatilla National Forest for 1977.

Figures 7 through 9 show the distribution of forestry burning activity on the West Side commercial forest lands of Washington and Oregon. Figure 7 shows the number of burns, Figure 8 the acres burned and Figure 9 tons of fuel burned. The degree of burning activity is shown by county for the years 1975 through 1977 and as an average of the 3-year period. In Washington only non-Federal commercial areas have been shaded in Figure 9, representing estimated tons of fuel burned, except for 1977, for which county-level figures were available for all burns on the West Side. During the period 1975-1977, an average of approximately 3900 burns were conducted each year on the West Side, 2769 in Oregon and 1090 in Washington. An average of 138 thousand acres were burned annually, 88 thousand in Oregon and 50 thousand

---

[1] As a result, the sum of individual county figures is less than the indicated West Side total.

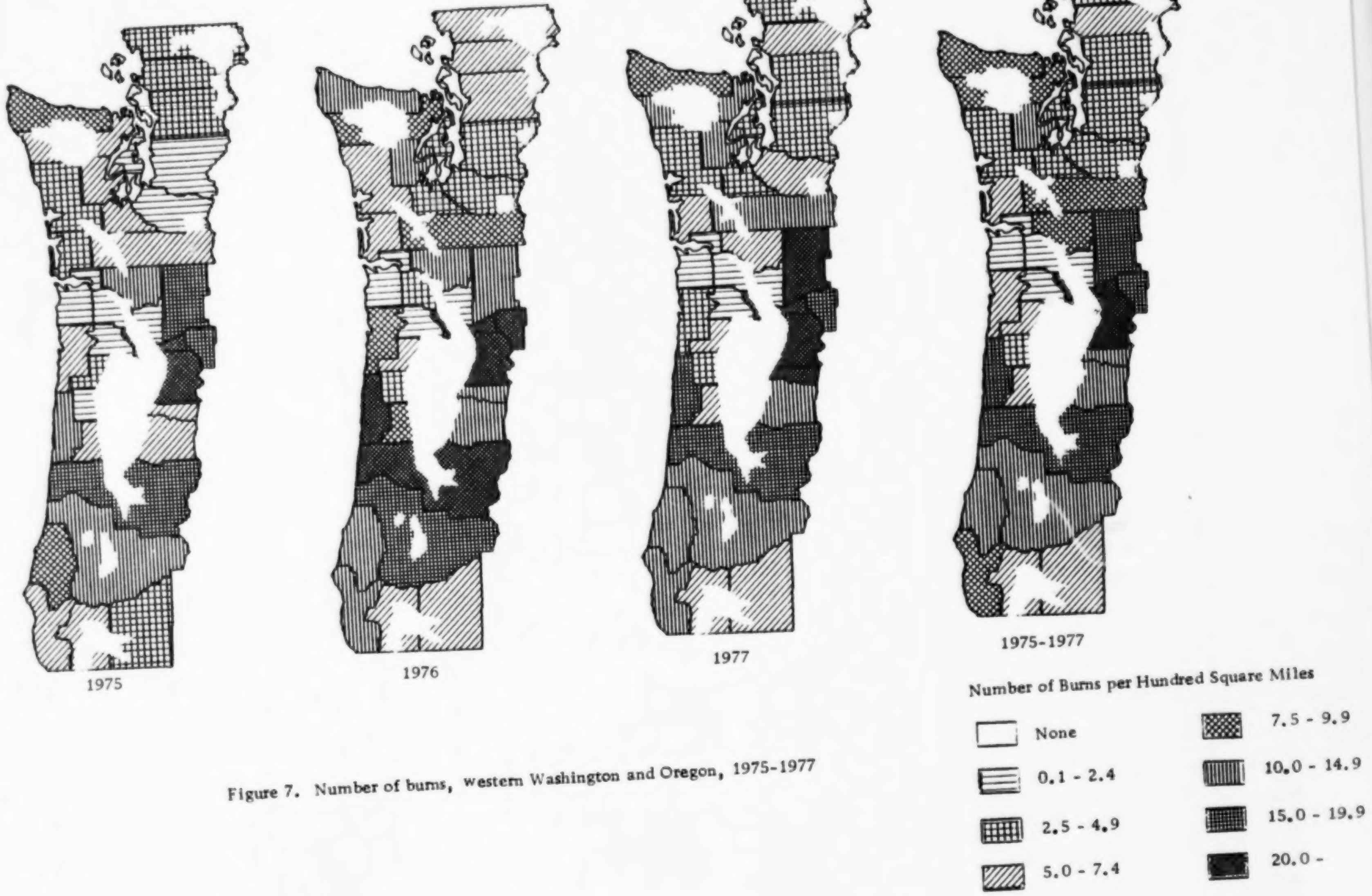

1975
1976
1977
1975-1977
Number of Burns per Hundred Square Miles
None
0.1 - 2.4
2.5 - 4.9
5.0 - 7.4
7.5 - 9.9
10.0 - 14.9
15.0 - 19.9
20.0 -

Figure 7. Number of burns, western Washington and Oregon, 1975-1977

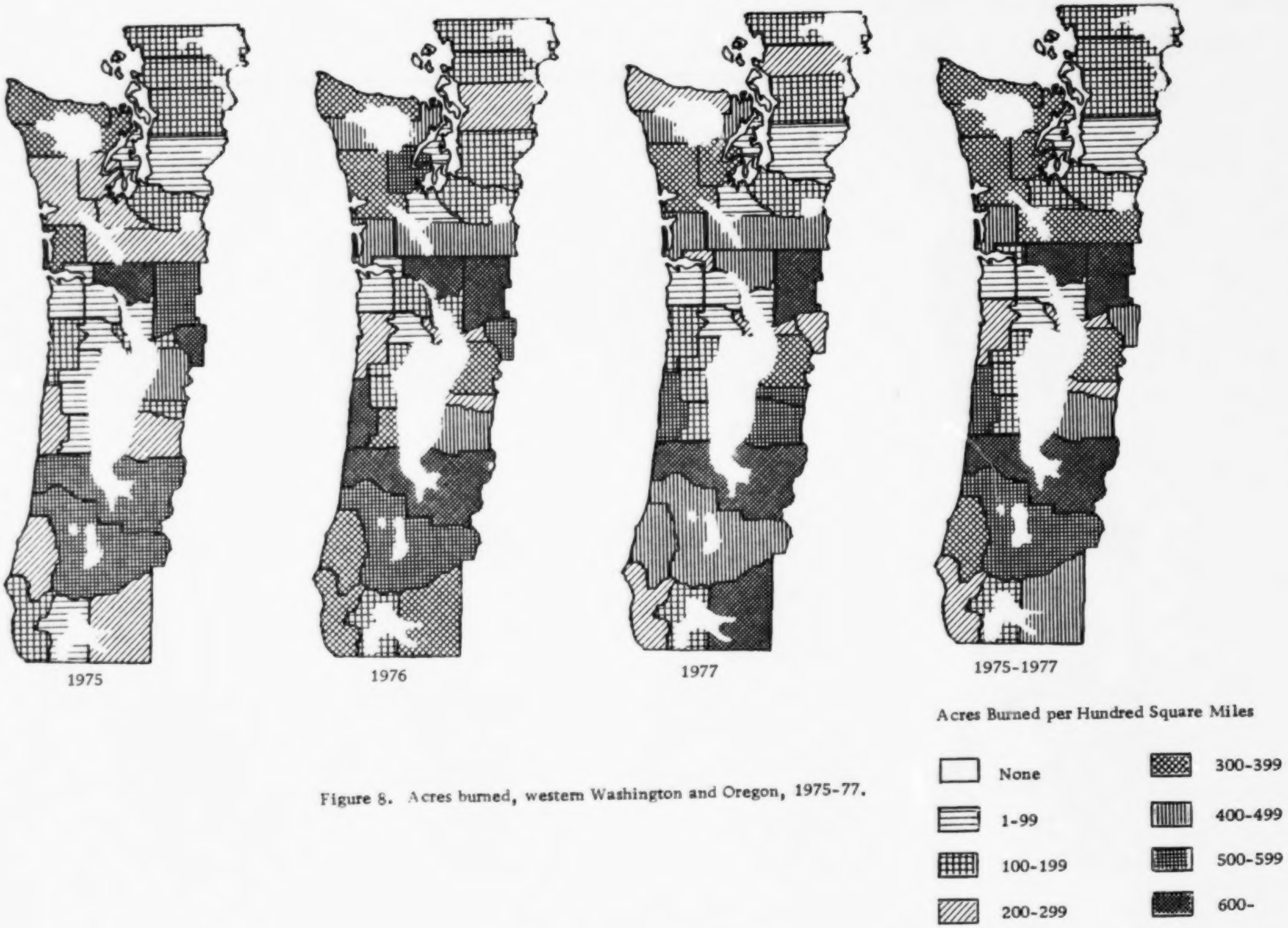

1975
1976
1977
1975-1977
Acres Burned per Hundred Square Miles
None
1-99
100-199
200-299
300-399
400-499
500-599
600-

Figure 8. Acres burned, western Washington and Oregon, 1975-77.

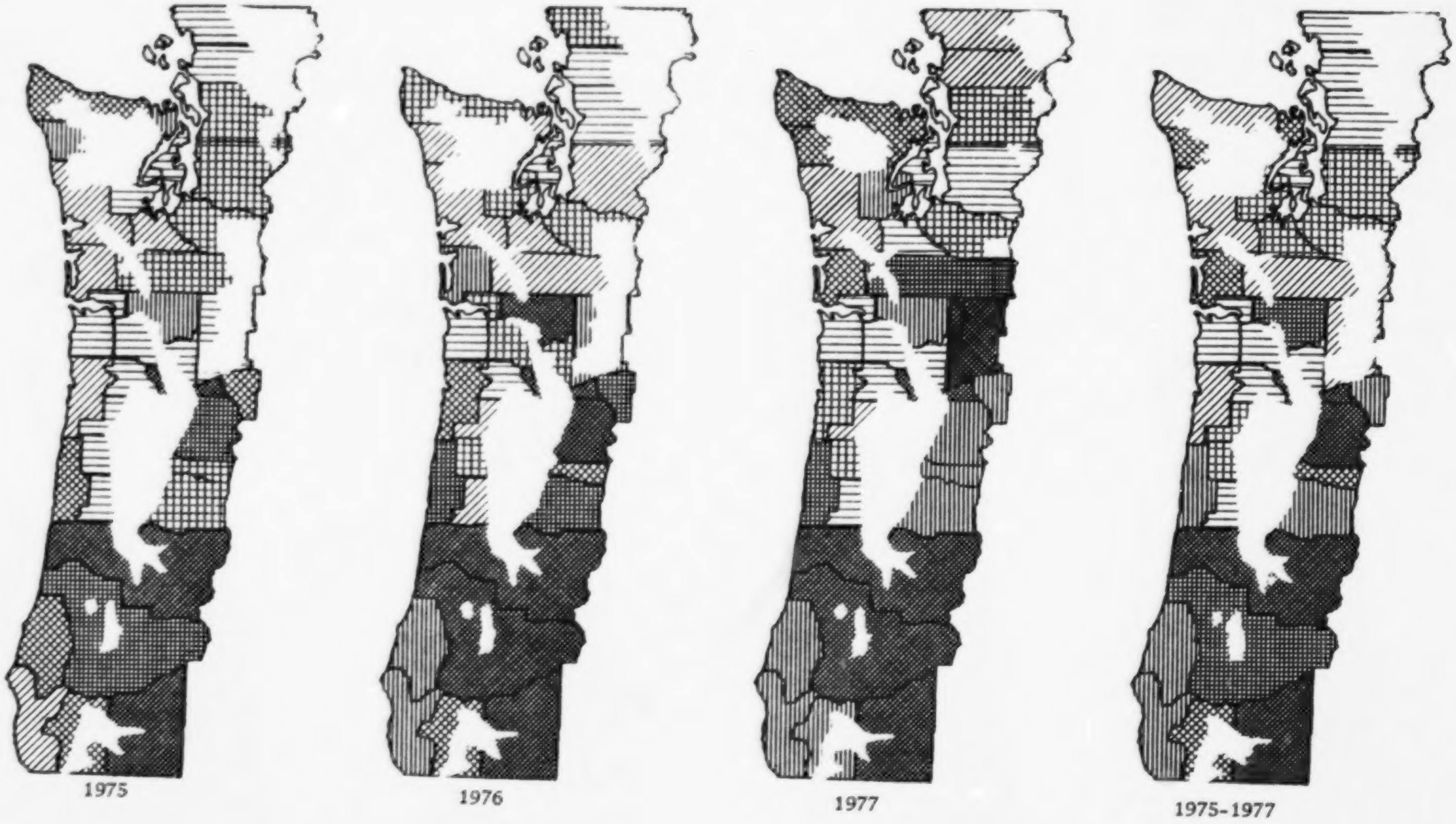

1975
1976
1977
1975-1977
Estimated Tons of Fuel Burned per Hundred Square Miles
☐ None
▤ 1 - 2,499
▦ 2,500 - 4,999
▨ 5,000 - 7,499
▩ 7,500 - 9,999
▥ 10,000 - 14,999
▦ 15,000 - 19,999
■ 20,000 -

Figure 9. Estimated tons of fuel burned, western Washington and Oregon, 1975-1977

in Washington. An estimated 5.1 million tons of fuel were burned, 3.5 million in Oregon and 1.6 million in Washington. Although these figures indicate more burning activity in Oregon than in Washington, on a unit area basis the two states are comparable. Oregon burns 6.1 thousand acres per million acres of commercial forest land and Washington burns 5.0 thousand acres per million acres of commercial forest land. Washington reported 1100 burns; considerably fewer than the 2800 burns reported by Oregon. The average size of burn blocks was 46.3 acres in Washington versus 31.8 acres in Oregon. However, average estimated fuel burned per acre was 39.9 tons in Oregon versus 31.9 tons in Washington.

East Side data available from the Oregon and Washington Smoke Management Programs indicate considerable forestry burning in Washington and comparatively little in Oregon. During the 3-year period from 1975 to 1977, an average of nearly 62 thousand acres were burned annually in eastern Washington, consuming an estimated 1.5 million tons of fuel. These figures do not include burns by the USDA FS in the Colville and Umatilla National Forests for all 3 years. The Oregon Smoke Management System (OSMS) reported 3637 acres were burned annually on Oregon's East Side, consuming an estimated 160 thousand tons of fuel, during 1975-1977. However, these figures do not include forestry burning in the large portion of eastern Oregon which is not within the jurisdiction of the Oregon Smoke Management Plan.

On the West Side, Douglas County, Oregon reported 22,480 acres burned; the greatest number of acres burned of the two states during the period 1975-1977. Lane County, Oregon was close behind reporting 22,362 acres burned. However, these two counties also have approximately twice as much commercial forest area as any other county in the two states. On a unit area basis, Douglas and Lane Counties were also high in burning activity, reporting 499 and 627 acres burned per 100 square miles of commercial timberland during 1977. Cowlitz County, Washington showed the greatest level of burning on a unit area basis, with 785 acres burned per 100 square miles of commercial timberland. Other counties reporting high levels of burning activity were Hood River, Oregon; Linn, Oregon; and Skamania, Washington.

The largest number of burns per unit area was in Clackamas County, Oregon with 27 burns per 100 square miles, Multnomah County, Oregon with 24 burns per 100 square miles and Skamania County, Washington with 17 burns per 100 square miles.

Estimated tons of fuel burned per unit area was greatest in Multnomah County, with more than 30 thousand tons of fuel burned per 100 square miles. Other counties with high estimated tons of fuel burned were Clackamas, Douglas, Jackson and Lane, in Oregon, and Cowlitz in Washington.

Principals Doing Burning

Table 4 presents the ownership of commercial forests in Washington and Oregon by broad ownership classes. On the West Side of the two states, 28.8 percent of commercial forest is owned by the U.S. Forest Service, 52.5 percent by private landowners and the forest industries, and 18.7 percent by other public agencies including Bureau of Indian Affairs, Bureau of Land Management, the State government, and municipalities. Figure 10 shows in greater detail the commercial and noncommerical land ownerships on the West Side of the two states.

TABLE 4. AREA OF COMMERCIAL TIMBERLAND BY OWNERSHIP CLASS
(In Thousands of Acres)

	National Forest	Other Public	Forest Industry	Other Private	Total
Oregon:					
West Side	4645	2876	3625	3238	14384
East Side	6993	584	1627	1378	10582
Total	11638	3460	5252	4616	24966
Washington:					
West Side	2365	1681	3634	2296	9976
East Side	3107	2266	735	2200	8308
Total	5472	3947	4369	4496	18284
Grand Total	17110	7407	9621	9112	43250

Sources: Washington Forest Productivity Study, Phase I Report, June, 1975, prepared under Project NR-1014 by the Department of Natural Resources of the State of Washington.

Timber Resource Statistics for Oregon, January 1, 1975, Bassett, P.M., and G. A. Choate, USDA Forest Service Resource Bulletin PNW-56.

Of the 138 thousand acres burned annually on the West Side, 84 thousand acres or 61 percent of the total is burned by the USDA FS. On the West Side the USDA FS is the dominant user of forestry burning. In Washington, 18 thousand of the 50 thousand acres are burned by the USDA FS, while in Oregon 66 thousand of the 88 thousand acres are burned by the USDA FS. A breakdown of the remaining 22 thousand acres in Oregon between private and State is not available from the OSMS. However, in Washington nearly 20 thousand acres were burned by the private sector, in comparison to 8 thousand acres by the State. Hence, in western Washington, the dominant principle in forestry burning is the private sector, although the USDA FS is a close second.

Although the USDA FS is the principal user of forestry burning on the West Side, only 28.8 percent of commercial forest lands are National Forests. In terms of burning activity per unit area, the USDA FS burned an annual average of 765 acres per 100 square miles of commercial forest land, while

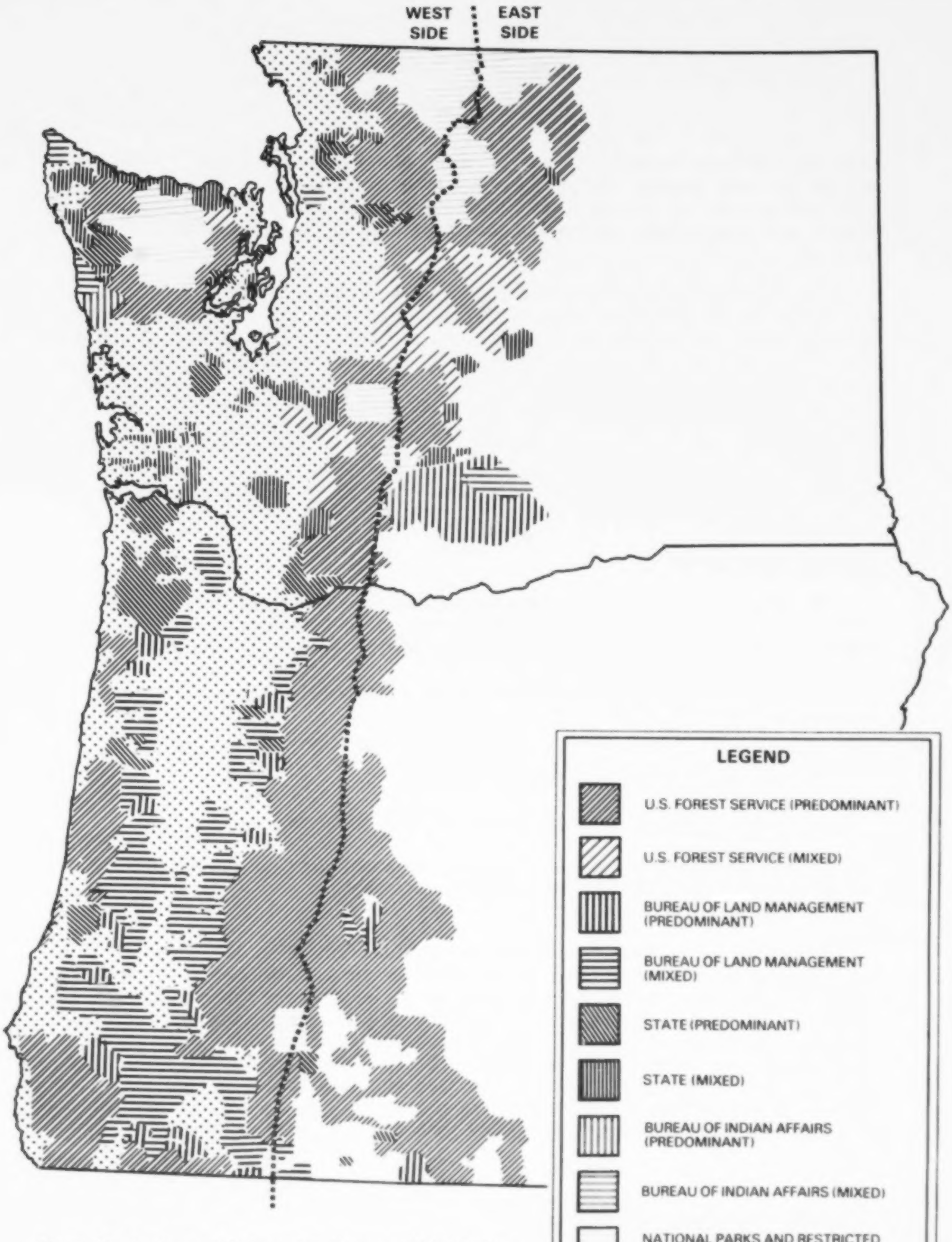

WEST SIDE
EAST SIDE
LEGEND
U.S. FOREST SERVICE (PREDOMINANT)
U.S. FOREST SERVICE (MIXED)
BUREAU OF LAND MANAGEMENT (PREDOMINANT)
BUREAU OF LAND MANAGEMENT (MIXED)
STATE (PREDOMINANT)
STATE (MIXED)
BUREAU OF INDIAN AFFAIRS (PREDOMINANT)
BUREAU OF INDIAN AFFAIRS (MIXED)
NATIONAL PARKS AND RESTRICTED FEDERAL LANDS
PRIVATE

Figure 10. Land ownership in western Oregon and Washington.

state and private sectors burned 201 acres per 100 square miles. A possible reason for this greater use of forestry burning by the USDA FS is the location and terrain of the National Forests. Much of the USDA FS lands are remote and mountainous, making residue treatment methods other than slash burning more difficult.

Most of the 62,264 acres treated by burning on the East Side of the two states is in Wasington with 61,627 acres burned. Of this, 76 percent of acreage burned on Washington's East Side is carried by the Bureau of Indian Affairs, 15 percent by the U.S. Forest Service and 8 percent by the private sector. Burning by the State on the East Side is negligible. Although the amount of burning on Washington's East Side decreased from 1975 to 1977, the amount of burning by the USDA FS, the State, and the private sector increased steadily over the period. In 1975 these sectors accounted for approximately 5600 acres. In 1977 they accounted for nearly 26,000 acres. During the same period, reported burning by the BIA decreased from 69 thousand to 47 thousand acres, more than offsetting increases by the other sectors.

Type of Fuel Burned

The relationship between the type of fuel burned and pollutant emissions is discussed in Section 3. Among the parameters describing forestry fuels' composition which are potentially important to emissions are:

- Material type (wood fiber, bark, pine needles, etc.)
- Tree species
- Size of fuel (diameter, length)
- Age (indicating whether fuel is dry, decayed, etc.).

The Smoke Management Programs of Oregon and Washington do not collect data on the type of fuel burned and explicit data on this variable are not currently available.

One approach to estimating the type of fuel burned by tree species is to assume that logging residue is of the same type as the harvested tree. Data are available on the type of tree harvested and are presented in Table 5. Most forestry burning in western Oregon is for slash removal following timber harvesting. In 1976, approximately 88 percent of forestry burning acreage within the jurisdiction of the Oregon Smoke Management Program was for slash disposal.[2] However, it does not necessarily follow that slash burned is of the same type as the tree harvested. A study of forest residue created during 1973 estimated that 60 tons of slash were created for every

---

[2] ITF-FSU, Final Report, 1977, p. 10.

TABLE 5. SUMMARY OF TIMBER PRODUCTION BY TYPE OF TREE (1000 Board Feet)

Tree Type	Oregon*	Washington †
	WEST SIDE	
Softwoods	8,086,400	5,015,516
Douglas-fir	N/A	2,240,104
Hemlock	N/A	1,804,339
Sitka Spruce	N/A	92,465
Cedar	N/A	513,427
True Firs	N/A	269,086
Other Conifers	N/A	96,095
Hardwoods	85,000	156,642
Red Alder	N/A	143,420
Black Cottonwood	N/A	6,388
Big Leaf Maple	N/A	1,881
Other Hardwoods	N/A	4,953
	EAST SIDE	
Softwoods	2,123,500	1,012,746
Ponderosa Pine	N/A	317,002
Western White Pine	N/A	15,960
Douglas-fir	N/A	324,542
Western Larch	N/A	87,919
Hemlock, True Fir	N/A	181,537
Other Conifers	N/A	66,771
Lodgepole Pine	N/A	19,015
Hardwoods	-	147
Black Cottonwood	N/A	13
Other Hardwoods	N/A	134

* Timber Resource Statistics for Oregon, Bassett, P.M., and G.A. Choate, USDA Forest Service Bulletin PNW-56, January 1, 1973.

† Timber Harvest Report, 1974, State of Washington Department of Natural Resources.

100 tons of timber harvested (Van Sickle 1973). Of these 60 tons, approximately 13 were growing stock residues. Of the remaining 47 tons, 11 were nongrowing residues greater than 4 inches in diameter, 17 tons were nongrowing residues 1 to 4 inches in diameter, and 19 tons were uncut small or undesirable trees. These figures indicate that the major portion of slash resulting from timber harvest is not residues from the harvested tree. This may be particularly true of old-growth stands which dominate the National Forests. The type of tree harvested may be an unreliable indicator of fuel burned.

Much research has been performed on the analysis of residues with a view toward fuller utilization. However, these studies typically exclude the fine residues which are the major components of available fuel, since these are the least potentially utilized. A study of residue by Howard (1973) specifically excluded material less than 4 inches in diameter or 4 feet in length. The literature does not reveal specific studies that address the composition of combustible fuel in forestry burning.

Another approach to evaluating the type of species burned is to compare the location of burning to tree stand maps. This approach is considered unreliable for the following reasons:

1. The vegetation map (see Figure 3) is at best a rough approximation of vegetative type. Only in carefully managed second growth areas are tree stands relatively pure.

2. As pointed out in the previous paragraph, the slash resulting from harvesting is not necessarily related to the dominant tree type in the stand.

The following conclusions by Howard (1973) are potentially relevant to determining the type of fuel burned:

- A large component of residue on USDA FS lands is decadent, old growth material. The average age of National Forests sampled was 260 years, in contrast to an average age of 140 years in private lands.

- The amount of residue material was greater on National Forest lands than on private lands by more than a factor of two.

- In the ponderosa pine region of eastern Washington and Oregon, more than half of the slash created consisted of whole trees or tree tops left after logging.

- The residue created on the East Side tended to be smaller than on the West Side.

Burning Techniques Used

The literature and available data from state and Federal agencies do not give detailed data on the use of different burning techniques in the Pacific Northwest. The following summarizes what is known about the use of broadcast and pile burning in the region:

- On the East Side, the principal agency conducting burning is the BIA. The BIA uses mostly pile burning.[3]
- Statistical compilations of burn technique are not available for Washington's West Side. However, the 1977 Washington SMP Annual Report indicates that private and state agencies use mostly broadcast burning, while the USDA FS uses predominantly pile burning. State and private burning accounted for 29 thousand acres and an estimated 557 thousand tons of fuel burned during 1977. The USDA FS burned 19 thousand acres and an estimated 867 thousand tons of fuel.
- The Oregon Smoke Management System (OSMS) reported that 41.2 percent of the 98 thousand acres burned in Oregon during 1977 were broadcast burned. Hence, pile burning is the more dominant method in Oregon. Roughly the same percentages were reported for 1976, but the 1975 OSMS report indicated a considerably lower percentage of broadcast burning (32.1 percent).

TIMBER HARVEST ACTIVITY AND ITS RELATION TO FORESTRY BURNING

Two of the primary reasons for forestry burning are hazard reduction and stand regeneration. As a result, the locations of burn blocks may correspond to recently cut timber stands. However, forestry burning could not to be statistically correlated with timber harvesting activity on a county basis. This is possibly due to the small percentage of acreage burned per year in comparison to that harvested. For example, in 1975 a total of nearly 207 thousand acres were cut on the West Side of Washington.[4] However, only 44 thousand acres were burned. Areas harvested one year are not necessarily burned that same year. Some areas may not require slash burning due to high utilization or other more appropriate treatment methods. Also, some forestry burning is not directly related to harvesting, including underburning and brush land conversion.

---

[3] Washington Smoke Management Report, 1977.

[4] Timber Harvest Report, 1975, Washington Department of Natural Resources, p. 13.

SECTION 3

EMISSIONS FROM FORESTRY BURNING

INTRODUCTION

Until recently, measurements of emissions from open burning were largely limited to effluents which were also industrial pollutants governed by the National Ambient Air Quality Standards. Emphasis was usually on determination of emission factors, relating the quantity of effluent produced to weight of fuel burned. The emission factors reported in the literature are highly inconsistent and the reliability of these factors for estimating emissions from actual fires is questionable. Emission factors are being upgraded but much more effort will be necessary before satisfactory reliability is achieved. Interest in minor and trace emissions has been increasing over the past several years and has generated funding for study in this area. Sampling, sample preservation and analytical techniques are evolving which will eventually provide comprehensive characterization of emissions from open burning. However, unique, specially constructed facilities are required for such studies and few exist at the present time. Quantitative data relating emission rates of some trace emissions to burning conditions are being reported. The following section is an attempt to summarize the available emissions data and to assess the reliability of extrapolating laboratory results to field situations.

Variability and Complexity of Emissions

The three general burning techniques, broadcast, pile and understory, have distinct differences in total emissions as well as in the ratios of individual effluents. Emissions within each of these techniques are highly dependent on fire behavior and fuel conditions. Fire behavior can be controlled or predetermined, within limits, and prescribed burning is only carried out under specific fuel moisture and weather conditions. While these factors provide greater emissions predictability than is possible for wildfires, each fire has a unique emission profile.

Discussion of the complexity of the emissions from open burning of forest products is prominent throughout the literature concerned with forest burning. The article of Tangren et al. (1976) includes a summary of the burning process and one of the most recent, concise discussions in this area. The authors point out that over 200 chemical compounds have been identified in wood smoke in contrast to over 1,200 in tobacco smoke. This difference merely reflects a difference in research emphasis and the number of compounds identified in smoke from forest burning can be expected to increase by as much as an order of magnitude as sampling and analytical techniques are improved. The emissions are not only chemically complex but size, shape, porosity, density and other physical properties of smoke particles are also highly variable. A number of the compounds emitted are photochemically reactive and the character of a smoke plume changes with residence time in the atmosphere. Both the fire and smoke plume are dynamic entities undergoing multiple reactions and interactions. The result is a composite emission which cannot be completely characterized with present technology.

A mathematical description of forest fire emissions was attempted by Becker (1973) as part of an EPA-sponsored study. The model, utilizing many simplifying assumptions, focused only on the major aspects of the emissions but could not be completed because of a lack of definitive data. Mathematical description of the emissions from forestry burning is highly complex and the data base has not expanded greatly in the past 5 years. It is therefore doubtful that a mathematical model with reliable predictive value can be constructed on the basis of presently available data.

Emission Factors

In the case of forestry burning, an emission factor is an estimate of the amount of emissions released into the atmosphere in relation to the amount of fuel burned. The factor is usually expressed as pounds of emission per ton of fuel burned, calculated on a dry-weight basis. Total emission is usually obtained by multiplying the emission factor by an estimate of the average quantity of fuel burned per acre and the total number of acres involved. Historically, there has been great divergence in assignment of emission factors to forest burning as well as uncertainty in estimation of the quantities of fuel burned. Particulate emissions from fires have been measured more extensively than most other effluents. The general sampling and analytical techniques for measurement of particulate emissions from various sources have been fairly well standardized for many years. Despite the relative ease of measuring particulate material, various comprehensive investigations have produced widely different estimates of the emissions of particles from forest fires. The historical inconsistency in these estimations is illustrated in Table 6, which, along with the footnote, is taken directly from a recent discussion by Ward et al. (1976).

TABLE 6. ANNUAL FOREST FIRE PARTICULATE PRODUCTION (TONS/YR.)
(Ward et al. 1976)

Reference	USA Estimate	Global Estimate
Vandegrift (1971)	54×10^6	
Hidy and Brock (1970)	15×10^6	150×10^6
Hoffman (1971)	6.7×10^6	
Cavender et al. (1973)	2.0×10^6	
Robinson and Robbins (1971)	0.7×10^6	3×10^6
Yamate (1975)	0.5×10^6	

To put these figures in a proper perspective, the estimate of 54×10^6 tons/yr for forest fires alone may be compared to the 27.3×10^6 tons/yr of particulates for all primary sources, including forest fires for the year 1969. (Cavender et al. 1973).

The discrepancies shown in Table 6 are the result of differences in method of computation, use of different emission factors, variations in the number of acres burned in the years on which the estimates were based and differences in estimates of the quantities of fuel burned per acre. The two arbitrary considerations, selection of emission factors and the method of computation, account for most of the variation shown. The compilation illustrates the confusion which has been prevalent in projecting forest fire emissions and shows a need for standardization of emission factors and of methods for applying these factors in estimating total emissions.

In general, emission factors are being updated as laboratory-scale burning facilities are made more representative of field conditions. The reliability of extrapolating laboratory results to obtain emission factors is also being improved through correlation with data obtained from field measurements. However, a great many more emission measurements from actual prescribed fires will need to be carried out before complete emission patterns can be reliably projected from burning prescriptions.

Determination of Emission Factors--

Emission factors have generally been determined from laboratory-scale studies in which burning was carried out under controlled conditions. The burning techniques and facilities described by Darley et al. (1966), Benner et al. (1977), Ward et al. (1974) and Yamate (1973) are representative of those which have been used to derive emission factors. The burning tower described by Darley et al. (1966), in some cases including the modifications indicated by Darley and Biswell (1973), has been used extensively for determination of factors for leaves, agricultural refuse and forest litter. The results obtained in numerous studies by various investigators using the burning tower have been summarized by Wayne and McQueary (1975). This facility approximates field conditions more closely than most laboratory installations. The quantity of fuel burned per test could range from 10 to 20 pounds of straw or grass to more than 50 pounds of woody material, which is a much higher capacity than that generally available for laboratory tests. In the tower installation, fuel was burned on a table equipped for recording weight changes on a 5-second frequency to monitor burning rate. Probes and instruments for monitoring various parameters of the burning process and for sample collection were mounted in a stack attached to a large funnel over the burning table.

Field measurements of emissions from actual fires require a great deal of preparation and are difficult to carry out, in comparison with laboratory measurements. As a result, few field measurements have been reported and the emission factors commonly quoted are based mainly on laboratory data. Boubel et al. (1969) and Darley et al. (1973) used sampling equipment mounted on a tower in plots of stubble and straw, which were then ignited and measurements were made as the fires burned past the tower. Ward et al. (1974) employed a grid of masts with samplers positioned at various heights to measure particle emissions immediately downwind from low-intensity line source backfires. Direct calculation of emission factors from field data has generally not been possible because the ratio of sample to total effluent could not be accurately defined. Downwind measurements of fire effluents can only be related to emission factors if the dimensions of the smoke plume and its rate of movement past the sampling point can be accurately established. While it is practically impossible to attain the accuracy and precision of controlled laboratory experiments under field conditions, the improved validity of conclusions based on field data offsets many imperfections in the measurements.

Reliability of Methods--

The diversity of emission factors reported in the literature does not inspire confidence in their overall reliability, particularly since most were derived from data obtained under closely controlled laboratory burning conditions. The laboratory-derived emission factors for leaves and agricultural refuse are considered relatively reliable, since these materials are usually loosely arranged or piled when burned in the field. This condition can easily be duplicated in burning laboratories and the data obtained are representative of field burning. Field conditions for burning forest fuels cannot be simulated as easily. Slash piles and broadcast slash burns involve tons of material, much of which is too large for a laboratory fire. Slash burning conditions are usually adjusted for maximum combustion efficiency and the resulting fires are hotter and smolder longer than those obtained from a few pounds of small fuel in a laboratory. Understory burning typically consumes small fuels in low intensity fires and should be more readily simulated in burning laboratories. However, the field fuels are generally the result of accumulation on the forest floor for a period of time and are variable in size, age, degree of compaction and stage of decomposition. They are also arranged in strata which cannot be simulated under laboratory conditions unless precautions, such as those described by Darley et al. (1973), are taken during sample collection.

Laboratory measurements of emissions from burning forest fuels can be made fairly easily and represent the most practical approach for identification of fuel and fire parameters which govern emission production. However, unavoidable differences between laboratory and field situations, with respect to fire behavior and fuel conditions, must be taken into account when extrapolating laboratory-dervied emission factors to field fires. For example, Sandberg (1974) measured particulate emissions of 6 to 24 pounds per ton in laboratory fires and 28 to 107 pounds per ton in field fires burning western logging residue. The emission factor of 17 pounds of particulate matter per ton of fuel, which has been used as the basis for estimating atmospheric emissions from forest fires (Yamate 1975), is compatible with the laboratory values but well below the range of the field emissions.

Influence of Fuel Type and Condition--

Fire behavior, the major determinant of emission factors, is highly dependent on fuel type, loading and conditions such as size, age, arrangement, compaction and moisture content. In developing emission factors for leaves under controlled laboratory conditions, Darley (1976) showed significant differences between leaves from different species in emissions of particles, carbon monoxide and hydrocarbons. Increasing moisture levels generally increased production of all three effluents, with particles showing the greatest increase. Burning compacted piles or green leaves produced much higher emissions than loosely piled dry leaves. These tests, carried out with material which is much more homogeneous than that typical in managed forestry burning, illustrate the dependence of emissions on small variations in fuel type and condition.

Many studies, for example, Darley et al. (1966), Gerstle and Kemnitz (1967), Sandberg (1974) and Ward et al. (1974), have shown emissions to be affected by the type and conditions of the material burned. However, many factors, such as arrangment of material, fuel loading and burning technique, also have pronounced effects on emissions. As a result of alteration of fire behavior, individual emission factors probably have little meaning when mixed fuels are burned. It is doubtful that the emissions from a mixture of leaves, needles and twigs would be predictable from emission factors obtained by burning samples of the three fuels separately.

Influence of Burning Techniques--

Burning techniques have a pronounced influence on both the total quantity of emissions and on the relative rate of production of individual effluents. As a broad generalization, factors such as high moisture, compaction and fire retardant, which increase residual, nonflaming combustion, tend to increase emissions. In a laboratory study of burning logging slash, Sandberg et al. (1975) found significant increases in emissions of carbon monoxide, hydrocarbon gases and particulate material from fuel beds which had been treated with diammonium phosphate flame retardant. Relative emission of unsaturated hydrocarbons was also higher from the treated beds. An important observation during these tests was that the initial 80 percent of the fuel burned produced only 20 to 30 percent of the hydrocarbon and carbon monoxide emissions, the major portion being produced during the die-down and smoldering phases.

The techniques used for burning have a significant effect on emissions. Laboratory studies may be carried out with fuel beds arranged on a slope to simulate head and back fires. Fires burning up the slope simulate head fires driven by a wind, while those burning down the slope simulate back fires progressing against a wind. The effect of slope on particulate emission factors from laboratory burning of various materials is illustrated in Table 7 taken from Ward et al. (1974).

The results lead to two general conclusions, fuel compaction increases particle emission and head fires emit greater quantities of particles than back fires. Data from laboratory studies of this type and field measurements have been used as the basis for predicting particle emissions from prescribed fires. Guidelines for predicting particle emissions and rate of fire spread as a function of available fuel and burning technique have been developed by Johansen et al. (1976) and constitute Chapter IV of the Southern Forestry Smoke Management Guidebook. The predictions require detailed information on fuel characteristics and fire behavior. Such information is presently available only for the southeastern United States and will need to be developed for individual fuel types and conditions in other regions before similar predictions can be applied in those areas.

TABLE 7. PARTICULATE EMISSION FACTORS (LB/TON, DRY BASIS;
Ward et al. 1974)

		Slope (percent)					
		Back Fire (simulated)			Head Fire (simulated)		
Fuel	Moisture (Percent)	-50	-25	0	+25	+50	+75
Loblolly pine (loose)	6	15	19	28	47	40	
Loblolly pine (loose)	10	13	20	37	67	55	
Loblolly pine (compacted)	18	28		86	123	158	152
Loblolly pine (branches & twigs) 1/4 - 1 in.)	15			6			
Goldenrod	10			6			
Mixed grasses (compacted)	12			34			
Hardwood leaves (red oak)	11			7			

MAJOR CONSTITUENTS OF EMISSIONS

Emission factors reported for the major effluents from forest fires are highly variable. Differences in fuel, fire behavior and burning techniques produce widely different emission patterns and use of a single factor for a given effluent is unrealistic. The approach suggested by McMahon and Ryan (1976), application of a range of factors whenever possible, shows the variation which may pertain and leads to conclusions which are less misleading than the use of single factors. The emission ranges for gases listed in Table 8 were suggested by McMahon and Ryan (1976) and represent the best general estimate of expected normal field emissions which can be made from data available at the present time. The range for particulate emissions was obtained from D.V. Sandberg who carried out a limited number of field measurements of emissions from burning western logging slash (Sandberg 1974).

TABLE 8. EMISSION RANGES (DRY WEIGHT BASIS)
(Gases - McMahon and Ryan 1976; Particulates - Sandberg)

Effluent	Emission Range (lb/ton of fuel)
Carbon dioxide (CO_2)	2000-3500
Water (H_20)	500-1500
Carbon monoxide (CO)	20-500
Particulates (TSP)	17-67*
Hydrocarbons (HC)	10-40
Nitrogen oxides (NO_x)	2-6

* Best available field range, revised in a private communication by D.V. Sandberg, March 1978.

The sulfur content of forest fuels is low in comparison with that of most other carbonaceous fuels. As a result, sulfur oxide emission from forestry burning is generally considered negligible. Airborne measurements of gases in plumes from five prescribed fires, reported by Radke et al. (1978), did not detect significant concentrations of gaseous sulfur in any of the plumes sampled.

Estimated total emissions of CO, TSP, HC and NO_x for Washington and Oregon are presented in Tables 9 and 10. The values shown were obtained by applying the ranges of emission factors in Table 8 to the estimated mass of fuel burned per county, by controlled forestry burning, in Washington and Oregon in the year 1977. Estimates of quantities of fuel burned were supplied by the USFS, the State of Oregon Department of Forestry and the State of Washington Department of Natural Resources. The three agencies agree that the estimated tonnages of fuel burned are not entirely accurate and that there probably has been a systematic tendency to overestimate available fuel. Opinions regarding the magnitude of the error of the fuel estimates differ to the extent that confidence limits cannot be established. Despite the fuel uncertainties and the broad ranges of emission factors on which Tables 9 and 10 are based, the values tabulated show the areas where emissions occurred and their relative magnitude from each of these areas.

Gases Emitted

Over 90 percent of the effluent mass from forest fires is CO_2 and H_2O. These gases are not normally considered pollutants in the context of impact on ambient air quality. Measurements of CO_2 production are frequently made to provide an index of combustion efficiency but H_2O emission is rarely measured. For the remaining gases, however, air quality and accurate emissions data are necessary for impact assessment.

TABLE 9. ESTIMATED EMISSIONS DUE TO FORESTRY BURNING, 1977 (annual average) IN WASHINGTON
(in tons of pollutant)

County	Estimated Tons of Fuel Burned	Carbon Monoxide		Particulate		Hydrocarbon		Nitrogen Oxides	
		Low	High	Low	High	Low	High	Low	High
Washington:									
Callam	95,940	959	23,985	815	3,214	480	1,919	96	288
Clark	700	7	175	6	23	4	14	1	2
Cowlitz	111,040	1,110	27,760	944	3,720	555	2,221	111	333
Grays Harbor	104,930	1,049	26,233	892	3,515	525	2,099	105	315
Island	0	0	0	0	0	0	0	0	0
Jefferson	80,460	805	20,115	684	2,695	402	1,609	80	241
King	21,950	220	5,488	187	735	110	439	22	66
Kitsap	2,490	25	623	21	83	12	50	2	7
Lewis	301,230	3,012	75,308	2,560	10,091	1,506	6,025	301	904
Mason	84,440	844	21,110	718	2,829	422	1,689	84	253
Pacific	71,455	115	17,864	607	2,394	357	1,429	71	214
Pierce	25,520	255	6,380	217	855	128	510	26	77
San Juan	0	0	0	0	0	0	0	0	0
Skagit	63,400	634	15,850	539	2,124	317	1,268	63	190
Skamonia	363,510	3,635	90,878	3,090	12,178	1,818	7,270	363	1,091
Snohomish	45,120	451	11,280	384	1,512	226	902	45	135
Thurston	5,440	54	1,360	46	182	27	109	5	16
Wahkiakum	4,150	42	1,038	35	139	21	83	4	12
Whatcom	41,580	416	10,395	353	1,393	208	832	42	125
Combined Western Counties	1,423,350	14,234	355,838	12,098	47,682	7,117	28,467	1,423	4,270
Combined Eastern Counties*	1,227,260	12,273	306,815	10,432	41,113	6,136	24,545	1,227	3,682
Statewide Total*	2,650,610	26,507	662,653	22,530	88,795	13,253	53,012	2,650	7,952

* Not including burning by U.S. Forest Service in the Colville and Umatilla National Forests of eastern Washington.

NOTE: Tonnage figures may be high. See page 43 for discussion of possible error.

TABLE 10. ESTIMATED EMISSIONS DUE TO FORESTRY BURNING, 1977 (annual average) IN OREGON
(In tons of pollutant)

County	Estimated Tons of Fuel Burned	Carbon Monoxide		Particulate		Hydrocarbon		Nitrogen Oxides	
		Low	High	Low	High	Low	High	Low	High
Oregon:									
Benton	5,002	50	1,251	43	168	25	100	5	15
Clackamas	199,684	1,997	49,921	1,697	6,689	998	3,994	200	599
Clatsop	14,855	149	3,714	126	498	74	297	15	45
Columbia	4,748	48	1,187	40	159	24	95	5	14
Coos	137,725	1,377	34,431	1,171	4,614	689	2,755	138	413
Curry	141,753	1,418	35,438	1,205	4,749	709	2,835	142	425
Douglas	888,965	8,890	222,241	7,556	29,780	4,445	17,779	889	2,667
Hood River	45,472	455	11,368	387	1,523	227	909	45	136
Jackson	448,012	4,480	112,005	3,808	15,009	2,240	8,960	448	1,344
Josephine	132,551	1,326	33,138	1,127	4,440	663	2,651	133	398
Lane	761,692	7,617	190,423	6,474	25,517	3,808	15,234	762	2,285
Lincoln	98,021	980	24,505	833	3,284	490	1,960	98	294
Linn	261,745	2,617	65,436	2,225	8,768	1,309	5,235	262	785
Marion	96,367	964	24,092	819	3,228	482	1,927	96	289
Multnomah	44,713	447	11,178	380	1,498	224	894	45	134
Polk	12,409	124	3,102	105	416	62	248	12	37
Tillamook	42,470	425	10,618	361	1,423	212	849	42	127
Washington	3,915	39	979	33	131	20	78	4	12
Yamhill	21,845	219	5,461	186	732	109	437	22	66
Combined Western Counties	3,361,944	33,619	840,486	28,577	112,625	16,810	67,239	3,362	10,086
Combined Eastern Counties	192,592	1,926	48,148	1,637	6,452	963	3,852	193	578
Statewide Total	3,554,536	35,545	888,634	30,214	119,077	17,773	71,091	3,555	10,664

NOTE: Tonnage figures may be high. See page 43 for discussion of possible error.

Gas Measurements and Reliability--

Measurements relating output of gaseous emissions to quantity of fuel burned have only been made under laboratory conditions. As indicated earlier, emissions derived in this way may not apply to field situations. Typical measurements and results for the major gaseous emissions are outlined in the following summaries.

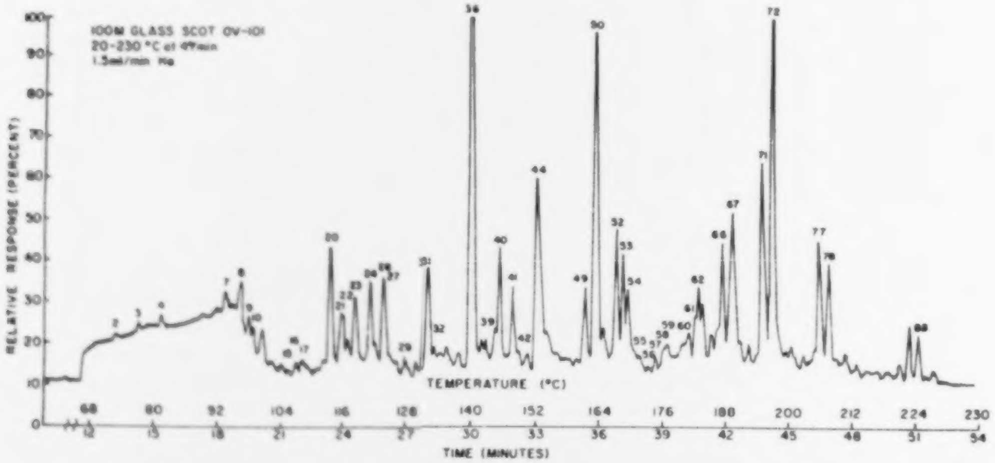
Carbon monoxide--The emission factors generally quoted for CO were derived from nondispersive infrared measurements of CO evolution from test fires in the burning tower described by Darley et al. (1966). The data included in reports by Darley et al. (1966), Gerstle and Kemnitz (1967), Sandberg et al. (1975) and Darley (1976) were obtained using this facility and measurement technique. Laboratory measurements of CO emissions reported by Benner et al. (1977), using different facilities and equipment, are in general agreement with the results from the burning tower.

Field measurements of CO in fires, adjacent areas and smoke plumes, such as those by Countryman (1964) and Fritschen et al. (1970), showed CO concentrations to diminish rapidly with distance from fires. Such measurements provide information on the concentrations of CO near fire zones but do not directly relate the mass of CO evolved to the quantity of fuel consumed. Field studies designed specifically for emission factor development will be necessary before CO emissions from forestry burning can be reliably predicted.

Hydrocarbons--Measurements of hydrocarbon emissions have generally been included in laboratory burning studies and the references cited for carbon monoxide have largely provided the data base for estimates of hydrocarbon emissions factors. The factors have generally been derived from flame ionization measurements of total hydrocarbons and nonmethane hydrocarbons. As indicated in the discussion by Hall (1972), flame ionization measurements include essentially all volatile organic compounds and the designation "hydrocarbons" as applied to wood smoke is misleading. Gas chromatographic analyses of grab samples taken at various stages of test fires have been used to identify predominant hydrocarbon emissions.

In studies of emissions from laboratory burning of logging slash, Sandberg et al. (1975) measured methane, ethylene, acetylene, total alkanes, total olefins and total alkynes. During the peak burning period, methane, ethylene and acetylene accounted for 50 percent of the flame ionization measurement. An additional 12 percent was composed of other alkanes, olefins and alkynes. The remaining carbonaceous material indicated by the flame ionization measurement, 38 percent, could not be accounted for by these classes of compounds. During the smoldering phases, the total hydrocarbons identified by gas chromatography constituted only 20 percent of the flame ionization value. It is apparent that the composition of the hydrocarbon effluent is greatly influenced by the stage of fire and that simple flame ionization measurements do not reflect changes in the composition of the hydrocarbon emission.

During the peak burning period, 38 percent, and during the smoldering period, 80 percent, of the hydrocarbon emissions could not be identified as simple alkanes, olefins and alkynes. An example of the complexity of the volatile organic emission is included in the report by McMahon and Ryan (1976), which presents a readout pattern from gas chromotographic/mass spectrographic analysis of smoke from laboratory burning of needles from loblolly pine (Pinus taeda L.). This pattern is reproduced in Chapter II of the Southern Forestry Smoke Management Guidebook (USDA Forest Service General Technical Report SE-10) and is shown in Figure 11. The complex array of compounds represents only the intermediate range (principally C_4 to C_{12}) of vapor components. It does not include low-molecular-weight oxygenated species, such as formic and acetic acids or reactive aldehydes, such as formaldehyde, acetaldehyde and acrolein. These low-molecular-weight compounds have frequently been identified in wood smoke and constitute a small, but significant, portion of the emission.



PEAK	COMPOUND
2	isopentane
2B	1-pentene
2C	furan
3	n-pentane
3A	isoprene
3B	acetone
4A	isopropanol
4B	cyclopentadiene
7	diacetyl
8	1-hexene
8A	methyl vinyl ketone
9	2-methylfuran
10	n-hexane
15	2,4-hexadiene
16	1,3,5-hexatriene
17	3-methylbutanal
20	benzene
21	cyclohexene
22	4-methylpentene
23	2,4-dimethylpentene
24	1-trans-2-dimethyl-cyclopentane
24A	acrylaldehyde (tent.)
26	2,5-dimethylfuran
26A	n-heptane
27	cis-2-heptene
29	2-vinylfuran
31	2,3-dimethyl-2-pentene
32	2,4-dimethylhexane
36	toluene
39	1-octene
40	2,3-dimethylhexa-1,4-diene
41	n-octane
42	2,3,5-trimethylfuran
44	furfural
49	ethyl benzene
50	p-xylene
50A	2-propionylfuran (tent.)
52	styrene
53	o-xylene
54	n-nonane
54A	2-isopropylfuran
55	anisole
56	2-methyl-5-isopropenylfuran
57	cumene
58	n-decane
59	camphene (tent.)
60	n-propylbenzene
61	m-ethyltoluene
62	p-ethyltoluene
66	1-decene
67	benzofuran
71	m-diethylbenzene
72	limonene
77	p-α-dimethylstyrene
78	n-undecane
88	n-dodecane

Figure 11. Chromatogram of organic vapors in loblolly pine smoke. Each peak represents a separate compound.

(Reproduced from Southern Forestry Smoke Management Guidebook, USDA Forest Service Gen. Tech. Report SE-10)

Nitrogen oxides--Emission of nitrogen oxides from burning forest fuels has not been widely studied. The factors quoted in various reviews are mainly from Gerstle and Kemnitz (1967) and Boubel et al. (1969). Oxidation of atmospheric nitrogen requires temperatures greater than 1500°C, which is considerably higher than the temperatures achieved in most prescribed fires. However, some nitrogen oxides are formed in these fires, possibly through involvement of hydrocarbon-free radicals, as indicated by Ay and Sichel (1976). Oxidation of fuel nitrogen is also possible. If this is the source, NO_x production should be fuel-dependent, with needles, foliage and duff producing relatively greater quantities than woody fuels. Benner et al. (1977), in a laboratory study of burning pine needles, reported emission factors of 6.3 and 3.1 pounds per ton of fuel for NO and NO_2, respectively. These values, from low intensity fires, are significantly higher than the NO_x emission factors listed in Table 8 and tend to support a fuel-related origin for NO_x. The conclusion stated by DeBell and Ralston (1970), that fuel nitrogen is released as N_2 on burning, is not supported by definitive data and is not widely accepted.

The source of the NO_x emissions remains a very open question. The two potential sources cited, oxidation of fuel nitrogen and involvement of hydrocarbon-free radicals in oxidation of atmospheric nitrogen are both fire- and fuel-dependent. It will be necessary to identify the source of NO_x and carry out a number of field measurements before reliable NO_x emission factors can be derived.

Oxidants--The action of sunlight on NO_2 in the presence of reactive hydrocarbons results in the production of ozone and organic oxidants. Potent eye irritants, peroxyacyl nitrates (PAN), are among the photochemical oxidants which may be produced. Olefins and saturated aromatic hydrocarbons are reactive and produce ozone by irradiation in the presence of NO_x. Formation of PAN-type compounds is associated with the presence of propylene, higher molecular weight olefins, and dialkyl- and trialkyl-benzenes. One of the main hydrocarbon effluents from forest fires, ethylene, results in the production of ozone, but not PAN, when it is irradiated in the presence of NO_x.

Radke et al. (1978) studied plumes from several prescribed fires of logging debris in western Washington. A 36 ppb increase in ozone concentration was measured 10 km downwind of an 86-acre fire. A 10 ppb increase in ozone was measured 13 km downwind of a plume of a much smaller fire. Radke et al. suggested that since forest fires are sources of NO_2, elevated ozone concentrations may be due to the greater amount of ozone needed to equilibrate the higher NO_2/NO ratio that exists in the plume.

Studies of the photochemical potential of forest fire smoke were reported by Benner et al. (1977). The effluent from burning 2-g quantities of pine needles was trapped in a chamber and subjected to alternating periods of darkness and artificial sunlight. The pollutant concentration followed the typical diurnal cycles found in Los Angeles-type photochemical smog. Light intensity equivalent to one-third of noon summer sunlight produced ozone concentrations of 30-40 ppb.

Evans et al. (1977) measured NO_2 and ozone concentrations in smoke plumes from large prescribed fires. Smoke from the plumes was also collected and subsequently irradiated. Irradiation increased the ozone concentration two to three times the concentration of olefins initially present; the rate of ozone formation was too rapid to involve photooxidation of ethylene. The presence of terpenes and unsaturated aldehydes was cited as a possible explanation for the rapid production of excess ozone. Smoke samples spiked with additional NO_2 produced significantly more ozone than samples without spikes.

Evans et al. (1977) measured maximum ozone concentrations of 65-70 ppb at a downwind distance corresponding to approximately 1 hour of irradiation by sunlight. Background levels were approximately 30 ppb. Ozone levels reached 100 ppb in plumes from high intensity burns. However, the strong convective rise caused the ozone formation at high elevations. Plumes from fuel reduction burns are normally trapped beneath elevated inversions. They may reach the ground as far as 50 km downwind, increasing the concentration of ozone at the surface. A correlation was observed between the depth of the elevated ozone layer and the effective depth of penetration of ultraviolet radiation through the plume. Evans et al. (1974) observed that the ozone layer developed at the top of the plume, with the thickness of the layer and the ozone concentration increasing downwind.

Measurements taken at various distances downwind of a plume showed ozone concentrations reaching maximum values after approximately 1 hour of irradiation (Evans et al. 1977). Irradiation of pine needle smoke rapidly produced maximum ozone concentrations which persisted for more than 10 hours before beginning to decline (Benner and Urone 1977). Irradiation of smoke held in a dark chamber for 24 hours produced ozone concentrations equivalent to those obtained by irradiation of fresh smoke. These results indicated that ozone precursors were not depeleted during the 24-hour period of darkness.

Forest fire smoke is photochemically reactive. If the observations of Evans et al. (1977) reflect typical field situations, photochemical production of ozone and oxidants in smoke is limited by NO_x, rather than reactive hydrocarbons. The photochemical reactivity of smoke drifting into industrial areas of high ambient NO_x levels could be significantly increased.

To predict the photochemical potential of forest fire smoke, it is necessary to carry out controlled laboratory chamber studies using smoke from typical fuels. The relative importance of NO_x and reactive hydrocarbons in limiting photochemical ozone production can then be determined. Field emission factors for NO_x and reactive hydrocarbons, and for the fuels and burning conditions of the Pacific Northwest, will also need to be defined.

Effects of Gases--

The health and environmental effects of CO and NO_x, which are also industrial pollutants, have been repeatedly documented by numerous studies and do not require further discussion in the present context. Some of the hydrocarbon and volatile organic emissions are unique to open burning and their effects have not been studied as extensively as those of the industrial pollutants.

Ethylene, one of the major hydrocarbon emissions, can cause injury to susceptible plants (AP-64, 1970). However, exposure to smoke from prescribed fires is generally considered too short for serious plant damage to occur, except in cases of poor ventilation when smoke stagnates at ground level in areas adjacent to a fire. Feldstein et al. (1963) estimated that the ethylene concentration 1 to 2 miles downwind from a fire burning 2000 tons of land clearing debris was 0.5 to 2 ppm and persisted for approximately 3 hours. Susceptible vegetation in the exposed area could have suffered ethylene damage in this time, though none was reported.

Relatively small quantities of potentially photochemically reactive compounds, such as olefins, diolefins and substituted aromatics, are released by forest fires. Downwind photochemical formation of ozone and other oxidants from these and nitrogen oxides is dependent on various plume and meteorological parameters. Evans et al. (1977) reported increased ozone concentrations in the upper layers of smoke plumes from field fires in Australia, and Radke et al. (1978) measured above-ambient concentrations of ozone in plumes from burning logging residue in Washington State.

The oxygenated organic compounds, though they constitute only a minor fraction of the gaseous emissions, cause most of the physical irritation associated with smoke. The major factors are probably water soluble, low-molecular-weight aldehydes, such as formaldehyde and acrolein, which are strong irritants to skin and exposed mucosa. Compounds of this type are reactive and their persistence as vapors in ambient air is relatively short. However, they readily adsorb onto smoke particles, which improves their stability and increases their toxicity. Impact on ground level air quality downwind from a fire is dependent on plume behavior and meteorological conditions.

Particulate Emissions

The emission of particulate matter from fires has been studied more extensively than the emission of gases. The particles generated by open burning have a high content of organic material and range in size from about 0.002 microns in diameter to very large particles. For practical purposes, only particles with aerodynamic diameters smaller than about 10 microns remain airborne long enough to impact on air quality. Larger particles fall out of the atmosphere fairly rapidly and can only be detected within short distances from prescribed fires.

Particle Measurements--

The most common apparatus for measurements of particulate matter in ambient air and source streams is the high volume sampler. Samples are collected on filters and the average particle load of the sample air is calculated on the basis of the weight of material collected on the filter. Measurements of this type have provided the basis for current air quality standards. However, mass measurements alone provide little information regarding the impact of the particles on air quality. There is increasing emphasis on including particle size distribution and chemical composition in assessments of air quality.

Multistage impactors with final filters have been used to fractionate particles from burning forest fuels on the basis of aerodynamic properties. Sandberg and Martin (1975) found the distribution of particle sizes shown in Table 11 in smoke from laboratory burning of Douglas-fir logging slash.

TABLE 11. PARTICULATE EMISSIONS FROM LOGGING SLASH (MASS BASIS)
(Sandberg and Martin, 1975)

Aerodynamic Particle Diameter	Average Percent
> 5.0 μ	8
1 - 5.0 μ	10
0.3 - 1.0 μ	13
< 0.3 μ	69

Examination of collected particles by electron microscope showed predominantly single spherical particles with diameters of approximately 0.1 micron, along with various aggregates of these particles. Similar results were reported by Ward et al. (1974) for low intensity prescribed fires in slash pine and palmetto-gallberry fuel types. Field measurements of particle size distribution on a number basis, using an electric charge mobility analyzer, were reported by McMahon and Ryan (1976). The average particle diameter reported was approximately 0.1 micron, which remained essentially constant for several different fuel types.

There is remarkable agreement between investigators studying various fuel types and burning conditions with respect to the size distribution of particulate emissions. This is in marked contrast to the total mass of particulate matter emitted, which is highly dependent on fuel types and burning conditions.

Effects of Particles--

Effects of particles on air quality are discussed in detail in Publication No. AP-49, "Air Quality Criteria for Particulate Matter," by the National Air Pollution Control Administration (1969). The publication includes individual chapters on various effects of particles. The key points of these are:

Solar radiation and climate--Atmospheric particles absorb and scatter sunlight, decreasing ground-level visible radiation. The problem is most acute in cities having atmospheric particulate loads of the order of 100 $\mu g/m^3$. In these, sunlight is reduced about 5 percent for every doubling in particle concentration. Particles serve as condensation nuclei and can influence precipitation patterns.

Visibility--Visibility is dependent on both the nature of particulate matter in the atmosphere and on the volume of air into which the particulates have been mixed. A measure of the volume of air available is the inversion height. Generally better visibility is associated with strong winds which provide better dispersion plumes. Particles in the atmosphere scatter light; as more light is scattered, the visibility becomes poorer. Particles of approximately the same size as wavelengths of visible light (0.4-0.8 μm) are the most effective scatterers of light, although particles from 0.01 to 10 μm contribute to scattering. Visibility markedly decreases when the relative humidity exceeds 70 percent due to hydroscopic particles absorbing water and increasing in size. Smoke from forestry burning has been observed to contain large numbers of particles in the size range below 1 μm diameter. Sandberg and Martin (1975) reported a majority (69 percent) of the particles from simulated fires to be less than 0.3 μm, 13 percent to be between 0.3 and 1 μm, 10 percent between 1 and 5 μm, and 8 percent greater than 5 μm.

Eccleston et al. (1974) made measurements of particle concentration, $C(\mu g/m^3)$, and the scattering coefficient, $b(m^{-1})$, in the plumes of nine Australian fires. A relationship of the form $C = 0.24b$ was developed. However, a more useful relationship would be between mass concentration and visibility. A simple proportionality between visibility and mass concentration implies similarity of the particle size distribution if the relationship is to be used at locations other than where it was developed. This is necessary since light scattering and mass concentration are functions of different ranges of particle size. Noll et al. (1968) expressed visibility in terms of mass concentration. In their study they assumed that mass concentration was proportional to the scattering coefficient and also that the theroretical relationship between visibility and the scattering coefficient took the form $V = 3.9/b$. Using measured data from four cities, a relationship was derived for each. Horvath and Noll (1969) obtained the formula for Seattle for $V = 1142/C$ where V is in miles and C is in $\mu g/m^3$. For a given mass concentration a measure of visibility can be obtained ± 50 percent when the relative humidity is less than 70 percent. These authors also assumed that the aerosol was well-aged and that the visibility was the average for the period of aerosol collection. Charleson (1968) reported visibility of 25 miles at 30 $\mu g/m^3$, 7.5 miles at 100 $\mu g/m^3$, and 3.75 miles at 200 $\mu g/m^3$. Charleson stated that visibility can vary by a factor of 2 for a given mass concentration due to differences in the particle size distribution. Eccleston et al. (1974) have collected scattering coefficient data for plumes in western Australia by means of a nephelometer. Figures 12 and 13 show scattering coefficient traces through plumes from large fires.

Weather modificaton effects--Since forestry burning introduces a large number of particles into the atmosphere, the impact on precipitation should be considered. Particles of < 0.1 μm serve as cloud condensation nuclei

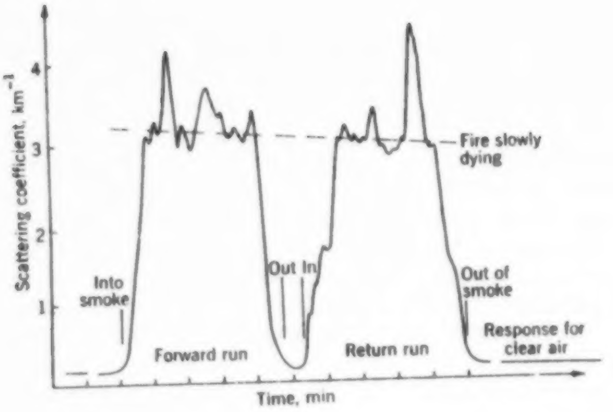


Figure 12. Nephelometer trace through plume (Eccleston et al. 1974).

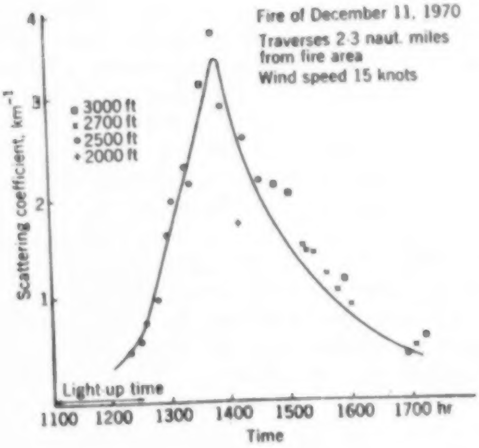


Figure 13. Nephelometer readings with respect to time (Eccleston et al. 1974).

(CCN) or ice nuclei in the precipitation formation process. Hobbs et al. (1970) observed that particles emitted from a large pulp and paper mill in Washington State broadened the rain droplet size distribution in clouds downwind from the mill; in theory, this should enhance precipitation. Hobbs and Radke (1969) found that CCN increased by a factor of 2.5 in smoke from slash burning. However, Ruskin (1974) found in the vicinity of a prescribed burn in the southeastern portion of the Olympic Peninsula that, although the CCN concentration measured 38 km downwind of the fire increased, the cloud droplet size was narrowed, therefore decreasing the efficiency of the rain-producing mechanism. After examining 60 years of rainfall records, Warner (1968) detected a reduction in rainfall downwind of sugar cane fires in Australia; this is consistent with the theory proposed by Hobbs and Radke (1969) that additional CCN compete for the available moisture, produce smaller droplets, and therefore hinder the droplet coalescence rainfall mechanism. Schaefer (1969) noted a similar effect downwind of brush fires in Africa.

Hobbs and Locatelli (1969) reported ice nuclei concentrations in forest fire smoke were four times that of ambient air in the Washington Cascades. However, this increase is small compared with the total increase in particulates.

Materials damage--High atmospheric particle loads correlate with increased corrosion of metal and surface damage to structures. The problem is common for corrosive industrial aerosols but is not a serious consequence of forest fire smoke.

Vegetation damage--Industrial aerosols containing phytotoxic materials cause serious damage to susceptible plants. Damage from wood smoke has not been demonstrated.

Respiratory deposition and clearance--Deposition is the process by which inspired particulates are caught within the respiratory tract and thus fail to exit with expired air. Factors which determine the fraction of inhaled particulates deposited, as well as their site of deposition, are respiratory tract anatomy, the effective aerodynamic diameter of particles, and the pattern of breathing. Clearance of deposited particles from the respiratory tract is dependent upon cilia and mucus transport to the pharynx, blood stream absorption, and direct expiration. In general, maximum respiratory tract deposition occurs for particles between 1-2 μm while minimum deposition occurs in the region of 0.5 μm diameter. The retention of particles with sizes less than 0.1 μm is as great as for those around 1 μm, with the smaller particles lodging primarily in the pulmonary compartment and the larger ones captured in the naso-pharynx area.

The occurrence of adverse human health which results from ambient particulate exposures is partially dependent upon the mechanisms used in the deposition and clearance of particles from the respiratory tract. Additionally, ally, there is increasing evidence that the combination of particulates with other atmospheric pollutants causes synergistic and antagonistic effects upon human health. As a consequence of increased particulate levels in the atmosphere, incidences of respiratory malfunctions and disease are evident. Under severe air pollution episodes, associated adverse health effects have been validated with studies showing increased incidence and severity of respiratory illness and increased death rates.

OTHER CONSTITUENTS

Minor and trace constituents emitted by forest fires have greater potential for producing adverse health effects than the major effluents. Volatile oxygenated organic compounds, such as acids, ketones, alcohols, aldehydes and furans are produced in the fires and partially absorbed in, or adsorbed on, condensing smoke particles. The particle-bound vapors retain activity longer than they would in the gaseous state and can be transported long distances from the fires. As indicated previously, the particles facilitate lung penetration, thereby increasing the apparent toxicity of absorbed materials. The oxygenated compounds are health hazards only under conditions of long exposure to relatively high levels. They may pose some threat to fire personnel but their content in diluted plumes is probably too low to cause measurable health effects at any appreciable distance downwind from a fire.

Polycyclic Organic Materials (POM)

These compounds are formed by pyrosynthesis in all inefficient combustion processes. Some of these compounds have been identified as carcinogens and others are suspected of carcinogenic potential. POM is organic matter that contains two or more ring structures and includes polycyclic aromatic hydrocarbons, polycyclic heterocyclics and various derivatives. It is separated into two classifications: PPOM, a solid which can be collected on glass fiber filters at ambient temperatures, and VPOM, a vapor which cannot be collected on glass fiber filters at ambient temperatures. A comprehensive review of PPOM was published by the National Academy of Sciences in 1972 and in a Technical Assessment Report by the U.S. Environmental Protection Agency in 1975. In most of the PPOM studies covered by these reports, benzo-a-pyrene (BaP) was used as an indicator substance for the PPOM family because of its carcinogenicity, ubiquity and distinctive chromatographic and spectral properties. Studies reviewed in the reports have indicated that PPOM is emitted as a vapor which may either condense on particles already present or form small particles of pure condensate. The half-life of PPOM in the atmosphere has been estimated at 100 hours under dry conditions, but may be much shorter. There is also evidence that some of the highly reactive compounds are degraded in the atmosphere by reaction with oxidants and by photooxidation.

The National Air Surveillance Network (NASN) has been collecting ambient air data on BaP concentrations since 1966. Estimates of emissions of BaP emission from open burning of agricultural wastes and other material have been made. Measurements of the emission of 12 PPOM, including BaP, from laboratory burning of pine needles in simulated head and back fires and three different fuel loadings have been reported by McMahon and Tsoukales (1978). The results from the latter study are reproduced in Tables 12 and 13. The data tabulated show the emission of all compounds to be highly dependent on fuel loading, burning conditions and stage of fire. The trends for BaP are representative of those of the other PPOM and range from 238 ng/g to 3454 ng/g in back fires and 38 ng/g to 97 ng/g in head fires. These trends are essentially the reverse of those for particulates, which range from 5 lb/ton to 21 lb/ton in back fires and 20 lb/ton to 118 lb/ton in head fires. However, the smoldering phase of head fires burning in pine needles produced higher emissions of both PPOM and particulate matter than the flaming phase.

The values recorded for BaP emissions from burning pine needles, for all but the lightly loaded back fire, are comparable with those cited by the National Academy of Sciences (1972) for open burning of landscape refuse (150 ng/g) and grass clippings, leaves and branches (346 ng/g). McMahon and Tsoukales caution that the results in Tables 12 and 13 were obtained with a single fuel type and that additional data on other fuel types and fire conditions will be required before PPOM emission factors for forest fires can be developed. The data reported are fire-dependent, suggesting that an emission range for PPOM will be more appropriate than a single factor.

Trace Elements

Emissions of trace elements from forestry burning have not been reported, but some measurements have been made on smoke from laboratory and field burning of agricultural refuse. Darley and Lerman (1975) obtained emission factors for the five metals listed in Table 14 for laboratory burning of Hawaiian sugar cane residues.

The residues were collected in Hawaii and shipped to the Riverside, California burning facility described by Darley and Biswell (1973), where the tests were carried out. On a mass basis, the metal emissions listed in Table 14 are very low and would not be expected to contribute significantly to the trace element background of rural air, which is due to natural sources.

Shum and Loveland (1977) measured emissions of 24 elements from burning grass fields in Oregon. The relative abundance of trace elements measured in the particulate effluent was comparable to that in the material being burned and the elements were almost entirely in the particulate fraction larger than about 2 μm. The authors concluded that the metals in the smoke were primarily due to incompletely burned plant material. The observation that trace elements are concentrated in the larger sized particulate emission suggests that field plume measurements, made at distances far enough removed from the fire to permit fallout of the large particles, will be necessary for development of element emission factors.

Emission of selenium, presumed to be SeO_2, from incinerator burning of wood chips, wood, sugar cane and trash has been reported by Shendrikar and West (1973). Smoke from wood chips and wood contained significantly higher concentrations of

TABLE 12. PPOM FROM BURNING PINE NEEDLES BY FIRE TYPE (ng/gram of fuel burned; dry-weight basis)*

	Backing Fires			Heading Fires		
	0.1 lb ft^2	0.3 lb/ft^2	0.5 lb/ft^2	0.1 lb/ft^2	0.3 lb/ft^2	0.5 lb/ft^2
Anthracene/Phenanthrene	12,181	2,189	584	2,525	5,542	6,768
Methyl Anthracene	9,400	1,147	449	1,057	4,965	7,611
Fluoranthene	14,563	2,140	687	733	974	1,051
Pyrene	20,407	3,102	1,084	1,121	979	1,133
Methyl Pyrene/Fluoranthene	18,580	2,466	1,229	730	1,648	2,453
Benzo(c)phenanthrene	8,845	1,808	468	244	142	175
Chrysene/benz(a)anthracene	28,724	5,228	2,033	581	543	636
Methylchrysene	17,753	1,891	877	282	1,287	1,559
Benzofluoranthenes	12,835	1,216	818	164	129	241
Benzo(a)pyrene	3,454	555	238	38	40	97
Benzo(e)pyrene	5,836	1,172	680	61	78	152
Perylene	2,128	198	134	33	24	46
Methylbenzopyrenes	6,582	963	384	65	198	665
Indeno(1,2,3-cd)pyrene	4,282	655	169	--	---	---
Benzo(ghi)perylene	6,181	1,009	419	--	---	---
TOTAL PAH	171,750	25,735	10,249	7,632	16,549	22,787
Total suspended particulate matter (TSP)	21 lb/ton	9 lb/ton	5 lb/ton	20 lb/ton	73 lb/ton	118 lb/ton
Benzene soluble organics	55 percent	50 percent	45 percent	44 percent	73 percent	75 percent

* Moisture content for all fires ranged between 18 to 27 percent.

Taken from McMahon and Tsoukalas (1978).

TABLE 13. PPOM FROM BURNING PINE NEEDLES BY FIRE PHASES (ng/gram of fuel burned; dry-weight basis)*

	Heading Fires by Phases					
	0.1 lb/ft^2		0.3 lb/ft^2		0.5 lb/ft^2	
	Flaming	Smoldering	Flaming	Smoldering	Flaming	Smoldering
Anthracene/Phenanthrene	1,621	7,049	865	9,046	2,351	8,791
Methyl Anthracene	539	3,872	667	8,193	1,909	11,447
Fluoranthene	445	2,317	244	1,516	622	1,331
Pyrene	750	3,078	342	1,454	888	1,291
Methyl Pyrene/Fluoranthene	455	2,383	494	2,501	1,036	3,396
Benzo(c)phenanthrene	228	397	77	189	179	173
Chrysene/benz(a)anthracene	472	1,324	230	769	628	980
Methylchrysene	263	497	343	1,989	466	2,290
Benzofluoranthenes	178	199	69	174	90	347
Benzo(a)pyrene	33	100	17	55	36	140
Benzo(e)pyrene	56	133	45	102	82	203
Perylene	38	33	14	32	27	61
Methylbenzopyrenes	19	397	52	304	75	1,069
Indeno(1,2,3-cd)pyrene	--	---	--	---	--	---
Benzo(ghi)perylene	--	---	--	---	--	---
TOTAL PAH	5,097	21,779	3,456	26,324	8,389	31,519
Total suspended particulate matter (TSP)	13 lb/ton	55 lb/ton	11 lb/ton	165 lb/ton	31 lb/ton	222 lb/ton
Benzene soluble organics	39 percent	48 percent	54 percent	76 percent	69 percent	76 percent

* Moisture content for all fires ranged between 18 to 27 percent.
Taken from McMahon and Tsoukalas (1978).

SeO_2 than that from the other two materials. The authors made no attempt to relate SeO_2 emission rate to combustion rate or mass of fuel burned.

TABLE 14. TRACE METAL EMISSIONS FROM LABORATORY BURNING OF SUGAR CANE (ng/kg; calculated from Darley and Lerman 1975).

	Nickel	Chromium	Beryllium	Cadmium	Copper
Whole Cane	0.16	0.05	0.02	0.18	0.56
Leaf Trash	0.12	0.04	0.04	0.28	0.82

FUEL COMBUSTION

If temperatures around 1000°C and complete aeration could be maintained throughout a fire, emission would consist almost entirely of CO_2 and H_2O. However, this condition cannot be attained in open fires, which are generally considered to pass through three burning stages. The following description of these three stages is quoted directly from the Southern Forestry Smoke Management Guidebook, Chapter II, by Tangren et al. (1976).

> "Pre-Ignition Phase (Pyrolysis Predominating)
> In this phase, the fuel is heated; volatile components move to the surface of the fuel and are expelled in the surrounding air. Initially, these volatiles contain large amounts of water vapor and some noncombustible organic compounds. As temperatures increase, hemicellulose, followed by cellulose and lignin, begin to decompose and release a stream of combustible organic products (pyrolysates). Because these gases and vapors are hot they rise, mix with the oxygen in the air, and ignite - producing the second phase.
>
> "Flaming Phase (Gas-Phase Oxidation Predominating)
> In the second phase, the temperature rises rapidly from the heat of exothermic reactions. Pyrolysis continues, but it is now accompanied by rapid oxidation, or flaming of the combustible gases being evolved in high concentrations. Carbon monoxide, methane, formaldehyde, organic acids, methanol, and other highly combustible hydrocarbon species are being fed into the flame zone. The products of the flame zone are predominantly carbon dioxide and water vapor. The water vapor here is not a result of dehydration as in the pre-ignition phase, but rather a major product of the oxidation of the fuel constituents.

> "Some of the pyrolyzed substances cool and condense without passing through the flame zone; others pass through the flames but only partially oxidize, producing a wide range of products. Many products of low molecular weight (methane, propane, etc.) remain as gases after cooling. Others, with higher molecular weights, cool and condense to form small, tarry, liquid droplets and solid soot particles as they move from the combustion zone. These condensing substances, along with the rapidly cooling water vapor that is being evolved in copius amounts, form the smoke that accompanies all forest fires.
>
> "Pyrosynthesis also occurs during this phase. Low-molecular-weight hydrocarbon radicals condense in the reducing region of the flames, leading to the synthesis of relatively large molecules such as the polynuclear aromatic hydrocarbons.
>
> "Glowing Phase (Solid Oxidation Predominating)
> In the final phase of combustion, the exposed surface of the char left from the flaming phase is oxidized, producing a characteristic glow. This continues, as long as temperatures remain high enough, until only small amounts of noncombustible material remain as gray ash. Many times the arrangement of the burning material is such that temperatures cannot be maintained, and black char is left instead of gray ash.
>
> "Fuel particles are not always consumed in a moving fire front. Because of the size, condition, or arrangement of these particles, some are pyrolyzed but not oxidized and others are only partially consumed before the flame is extinguished. From the heat still available after the flaming phase, these particles emit large amounts of smoke. Still other particles continue in flaming combustion after the flaming phase has ended. As a result dehydration, pyrolysis, solid oxidation, and scattered flaming often occur simultaneously during this last phase. Where this condition exists, that last phase is called smoldering."

The major portion of the emission from forest fires occurs during the pre-ignition and glowing phases. Cramer (1974) has pointed out a number of ways in which emissions can be minimized through adjustment of burning techniques to utilize the efficient flaming phase to maximum advantage. Piled fuels, in particular, burn more efficiently in larger fires because higher average combustion temperatures are attained. Large piles have proportionally less fuel near the edges, where it is subject to inefficient combustion. Maximum combustion efficiency in pile burning is achieved with a continuing fire to which fuel is added at a rate which maintains the fire in the flaming phase. Fuels such as duff and rotted wood tend to burn in the glowing phase and their inclusion in pile fires increases emissions. Head fires move rapidly and burn off the light fuels in a relatively cool, inefficient flame, leaving heavier fuel elements smoldering. Back fires progress more slowly and consume proportionally more of the available fuel during the flaming phase.

FUEL MOISTURE

The effect of fuel moisture on emissions has not been studied extensively. There appears little question that increased moisture decreases the quantity of available fuel and rate of fire spread, thus decreasing source strength and rate of emissions. However, the effect of moisture on emission factors has not been clearly defined. Darley (1976) noted marked increases in particulate and hydrocarbon emission factors for leaves when fuel moisture was increased from 10 to 20 percent. Particulate matter increased by as much as 400 percent and hydrocarbons by as much as 300 percent, although carbon monoxide showed only a 29 percent increase. Measurements of emissions from field burning of agricultural refuse reported by Carrol et al. (1977), also showed increasing fuel moisture to greatly increase emissions of carbon monoxide, hydrocarbons and particulate matter. The effect of fuel moisture on emissions was much more pronounced in head fires than in back fires.

Ward et al. (1974) showed higher particle emissions in simulated head fires in pine needles at 10 percent moisture than at 6 percent. The difference in moisture level did not affect particle emissions from simulated back fires in the same fuel. In measuring field emissions, the same authors noted a significant decrease in rate of fire spread and, consequently, rate of particle emissions with increasing moisture. However, the particle emission factors were similar at the two moisture levels. Studies reported by Darley et al. (1974) and Darley (1977) indicate that emissions of particulate matter, carbon monoxide and hydrocarbons increase with increasing fuel moisture for fine agricultural fuels but drying woody fuels below 35 percent moisture has little effect on these emissions.

SOURCE STRENGTH

Source strength can be defined and determined in a number of ways. Definitions generally include total emissions as well as emission rates. For point sources, such as power plants, both integrated emissions and emission rates are predictable from operating parameters and are usually monitored as part of the operating activity. Line sources, such as major traffic arteries, pose a more difficult problem. However, emissions are predictable from traffic patterns and fixed monitoring stations can be strategically placed along a route to document integrated and instantaneous source strength. The difficulty of predicting and measuring the strength of area sources, such as forest fires, is orders of magnitude greater than than point or line sources.

While the locations of prescribed fires are known, fixed monitoring installations are impractical because a given plot is burned only once in several years. Electric line power is not normally available near prescribed fires and any monitoring must rely on battery power or portable field generators. Since a fire only burns a plot once, there is no margin for error in deployment of monitoring instruments and no time for correction of malfunctions. Field monitoring of forest fires to determine source strength is therefore difficult, costly and uncertain. The approach taken by the southern region, monitoring a limited number of field fires in representative fuels under usual burning conditions to predict source strength, appears more reasonable than attempting to monitor all prescribed fires. Methods used to predict the emission of particulate matter from typical fires in southern fuels have been described in detail by Mobley et al. (1976). The major fire and fuel parameters that are important for predicting source strength are outlined in the following subsection.

Fire Behavior and Burning Technique

Emissions from fires occur in two phases which may take place simultaneously or sequentially. An actively burning fire front generates enough heat to entrain emissions into a convective column. The emissions are carried far from the fire by the resulting plume and are usually well dispersed before returning to ground level. A fire in the smoldering phase does not generate enough heat to produce a convective column. Emissions remain near ground level and can impact on air quality in areas adjacent to fires. Fires are thus composite sources with varying emission rates and plume rise that impact on air quality both near the fire and at greater distances. Consideration of source strength can emphasize either or both emission properties, depending on fire location, meteorological conditions and downwind smoke sensitivity.

Fire behavior and burning technique have a pronounced effect on source strength for any given fuel loading condition. Fuel moisture, particularly that of the litter layer and fine fuels, influences the rate of fire spread and the quantity of available fuel. With very wet fuels, the rate of fire spread is too slow to generate enough heat for formation of a convective column and the entire emission drifts from the fire zone at ground level. Back fires consume most of the available fuel in the flaming fire front. A high percentage of the emissions is entrained in the convective column if the fire intensity is adequate for formation of such a column. Head fires consume only fine fuels in the flaming front, leaving heavier fuels smoldering. As a result, head fires may consume only 50 to 80 percent of the available fuel during the advancing-front combustion stage. There is frequently enough heat in the advancing-front stage to entrain part of the residual stage emissions into the convective column (Johansen et al. 1976). In contrast, the mass ignition techniques typically employed for slash burning in the Pacific Northwest result in rapid formation of strong convective columns which entrain the major portion of the fire emissions.

Available Fuel Loading

Source strength, in terms of total emissions and emission rates, is highly dependent on fuel loading and arrangement, which determine fire behavior and largely govern selection of burning technique. Methods for estimating total and available fuel in the Pacific Northwest include those described by Beaufait et al. (1977), Brown (1974), Maxwell and Ward (1976a, b), and Hedin and Taylor (1977). The individual methods have varying utility and reliability for estimating quantities of available fuel and predicting fire behavior. Fuel loadings and emission factors are the major parameters governing source strength. Field emission factors for the fuels and burning conditions of the Pacific Northwest will need to be accurately defined. Methods for estimating available fuel in terms of type, size, arrangement and condition will need to be improved to serve as the basis for derivation of fire behavior models. The utility of such models for estimating source strength and predicting emission impact is a direct function of the accuracy of the emission factors and available fuel estimates. The models will need to be validated through selected field measurements of emission, heat evolution and fire spread rates. In the absence of such validated models for the specific fuels and burning conditions of the Pacific Northwest, source strength of individual fires can be guessed but not accurately estimated.

SECTION 4

IMPACT OF FORESTRY BURNING UPON AIR QUALITY

This section addresses the impact of forestry burning on air quality in the Northwest. The first subsection summarizes air quality problems as they relate to the attainment of National Ambient Air Quality Standards in Washington and Oregon. The second section describes the mechanics of pollutant transport and dispersion relative to forestry burning activity in the Northwest. The third section reviews studies which have attempted to assess the impact of forestry burning on air quality through various approaches. The final section discusses the relative impact of forestry burning in comparison to other emission sources.

CURRENT AIR QUALITY PROBLEMS IN THE NORTHWEST

Under authority of the Clean Air Act of 1970, the U.S. Environmental Protection Agency developed National Ambient Air Quality Standards (NAAQS), which established acceptable levels of five criteria pollutants. Standards are of two basic types, primary and secondary. Primary standards are established to protect the public's health and are based on scientific data published in air quality criteria documents. Secondary standards are designed to protect the public's welfare. Standards established for criteria pollutants are summarized in Table 15.

Under the Clean Air Act, individual states have the responsibility of bringing nonattainment areas into compliance with NAAQS and insuring that NAAQS standards are maintained. Attainment of NAAQS standards is determined by standard air quality monitoring techniques and, in some cases, by diffusion modeling techniques. The attainment statuses of areas within Oregon and Washington were recently published in the Federal Register[1] as required by the Clean Air Act Amendments of 1977, and are presented in Table 16. This table indicates that ambient levels of total suspended particulates (TSP), photochemical oxidants (O_x), and carbon monoxide (CO) represent major air quality problems within the two states.

---

[1] Federal Register, Vol. 32, No. 43, Friday, March 3, 1978.

TABLE 15. NATIONAL AMBIENT AIR QUALITY STANDARDS

Pollutant	Primary Standards	Secondary Standards
Total suspended particulate	Annual geometric mean of 75 μg/m^3 not to be exceeded	Annual geometric mean of 60 μg/m^3 not to be exceeded
	24-hour concentration of 260 μg/m^3 not to be exceeded more than once per year	24-hour concentration of 150 μg/m^3 not to be exceeded more than once per year
Sulfur dioxide	Annual arithmetic mean of 80 μg/m^3 not to be exceeded	3-hour concentration of 1300 μg/m^3 not to be exceeded more than once per year
	24-hour concentration of 365 μg/m^3 not to be exceeded more than once per year	
Carbon monoxide	1-hour concentration of 40 mg/m^3 not to be exceeded more than once per year	
	8-hour concentration of 10 μg/m^3 not to be exceeded more than once per year	
Photochemical oxidants	1-hour concentration of 160 μg/m^3 not to be exceeded more than once per year	
Nitrogen dioxide	Annual arithmetic mean of 100 μg/m^3 not to be exceeded	

TABLE 16. NAAQS ATTAINMENT STATUS FOR OREGON AND WASHINGTON
(X indicates attainment not reached at current time)

Area	Total Suspended Particulate		Sulfur Dioxide		Photochemical Oxidants	Carbon Monoxide *	Nitrogen Dioxide *
	Primary	Secondary	Primary	Secondary			
Oregon							
Portland - Vancouver AQMA ** (Oregon portion)		X			X	X	
Medford-Ashland AQMA **		X			X	X	
Eugene-Springfield AQMA **	X				X	X	
Salem					X	X	
Remainder of State							
Washington							
Seattle ***	X				X	X	
Renton		X					
Kent		X					
Tacoma ***	X		X				
Port Angeles ***		X					
Longview		X					
Vancouver	X				X		
Yakima						X	
Spokane	X					X	
Clarkston	X						
Remainder of State							

* Primary and secondary standards for these pollutants are identical.

** Air Quality Maintenance Area--an area defined by states for the purpose of air quality maintenance planning.

*** Different attainment statuses were published for localities within these urban areas. If both primary and secondary standards were violated, we have indicated only that primary standards were violated.

A few points should be made about the attainment status and its value as an indicator of air quality.

- First, attainment status can only be determined where air quality monitoring data have been collected or air quality models are used to estimate air quality levels. As a rule, air quality monitors are placed in populated areas.

- Federal law requires that all areas within states be designated as attainment, nonattainment, or nonclassifiable areas. Many of these areas are large and have relatively few monitors located within them. Hence the designation of nonattainment does not necessarily imply poor air quality throughout an area. Nor does the designation of attainment necessarily imply acceptable air quality through an area.

- On the other hand, a careful analysis is made of monitoring data before a designation of attainment or nonattainment is made. For example, if uncharacteristic meteorological conditions led to abnormally low or high air quality readings, this factor is taken into account in determining attainment status.

- Rural areas are generally not designated as nonattainment if it can be shown that particulate levels result from fugitive dust emissions. Rural, wind-blown dust is not believed to contain the same toxic pollutants and to have the same health impact as urban dust.[2]

The attainment status of an area represents the state's best evaluation of the air quality relative to NAAQS within populated locales.

In Oregon, major air quality problems exist in the urban areas of Portland, Salem, Eugene-Springfield, and Medford-Ashland. The problem appears to be most severe in the Eugene-Springfield area, where particulate, ozone, and carbon monoxide standards are exceeded. In Washington, five urban areas on the East Side and four areas on the West Side exceed NAAQS. Photochemical oxidant problems exist in the Puget Sound area of Seattle and Tacoma. Carbon monoxide exceedances occur in Seattle, Yakima, and Spokane. Particulate exceedances occur at every area reporting an exceedance of any type, except for Longview.

---

[2] Federal Register, Vol. 43, No. 43, March 3, 1978, p. 8963.

The Clean Air Act Amendments of 1977 require states to submit to EPA State Implementation Plans to achieve NAAQS primary standards within designated nonattainment areas, while maintaining standards in areas where NAAQS are not currently exceeded. These plans must be submitted to EPA by January 1, 1979. In order to develop strategies which are effective in achieving primary standards, states must be able to determine the contributions of various sources to air quality. One potentially significant source is forestry burning.

MECHANISMS BY WHICH FOREST BURNING IMPACTS AIR QUALITY

Combustion products including heat, water vapor, particles and gases are emitted into the atmosphere from an open fire and form a plume or cloud of material which is transported in a downwind direction by the wind. Meteorological parameters determine to what height this plume will rise and what its dimensions will be at downwind points. Numerous references appear in the literature regarding pollution observation studies in the vicinity of fires; mathematical models of plume behavior have been attempted to predict downwind pollutant concentrations. Such models must include features which will adequately describe the airflow within a forest, the airflow in complex terrain, to what height the plume will rise, and to what extent the plume will disperse pollutant material into the atmosphere by turbulence.

Smoke plumes can be quantitatively described with respect to size, composition, behavior and effects. Each of these characteristics is determined from several interrelated factors including type and quantity of fuel, burning phase of the fire, meteorological conditions, land slope and the type of fire.

The composition of the plume includes the chemical, heat, moisture and particulate content of the fire emissions. The composition and effects of forestry burning emissions are described in Section 3. This section discusses initial plume characteristics and how the meteorology and the terrain affect the transport, dispersion, deposition and transformation of the plume and hence its impact on air quality.

Plume Rise

Plume height is the height above ground level at which the vertical rise of the smoke plume stops. Plume height is determined by atmospheric stability, wind speed and heat release rate of the fire. Murphy (1976) measured plume rise from a 15 hectare burn in Georgia using an instrumented aircraft. Under the burn conditions, the plume rose to the top of the mixing layer within 8 km of the burn site. Figure 14 depicts the density of the smoke plume in a vertical section from transects made 1.6 km from the fire.

Nephelometer data showed the plume rapidly rising through the mixing layer and a plume width of approximately 2000 m measured 1.6 km downwind. The dimensions of the source are not given; however, the fire was estimated to be approximately 500 m across at the time of the measurements. Eccleston et al. (1974) described fires covering areas of 1400 to 8800 hectares (3500 to 22,000 acres) in western Australia. Plumes from the burns were measured from 1067 to 3048 meters (3500 to 10,000 feet) in altitude. A description of the existing meteorological conditions was not provided. Vines (1974) observed the behavior of plumes from burned areas of approximately 3000 hectares (7500 acres) containing approximately 45 x 10^3 kkg (50 x 10^3 tons) of fuel.

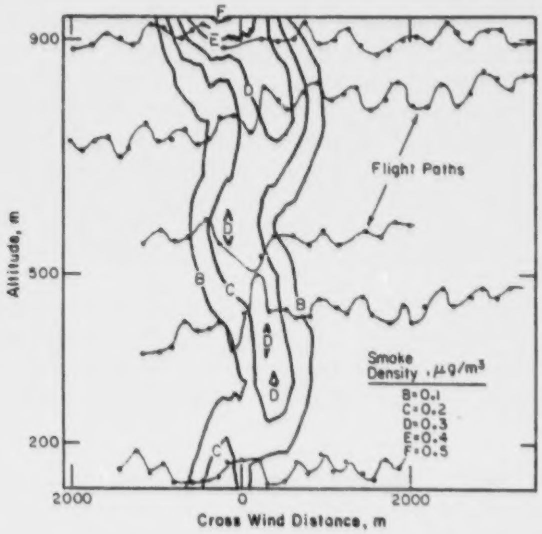


Figure 14. Vertical profile of smoke density (Murphy 1976).

Norum (1974) monitored 22 prescribed burns of approximately 4 hectares (10 acres) to relate fire intensity with convective plume height. Fuel quantities were measured before and after the burn and fuel moisture at the time of the burn. Convective column heights were determined from an aircraft. The relationship of fuel, fire and atmospheric variables to plume height was studied; convective plume height was more closely related to variables which control fire intensity, such as wind speed and fuel dryness, than to mixing depth.

Research by Briggs (1969, 1975) to determine plume rise from heated plumes emitted from chimneys is based on principles which should be applicable to forest burning. The Southern Forestry Smoke Management Guidebook (Pharo, Lavdas, and Bailey 1976) has adopted the Briggs method for estimating plume heights. However, in the South it is estimated that only 60 percent of the smoke from a prescribed fire is carried aloft by the convective uplift and attains the height predicted by the Briggs equations. The remaining 40 percent remains unentrained and drifts along the ground.

Lavdas (1978) made comparisons of plume heights observed from aircraft using estimates calculated by the Briggs equations. In all experimental cases, the Briggs estimates agreed with observations within a factor of two with both overprediction and underprediction occurring. Lavdas also formulated a plume rise model that accounts for the smoke not entrained by the rising convective column. The model allows 60 percent of the smoke to attain a Briggs plume height while 40 percent is assigned to a plume height of zero. This approach yields satisfactory ground-level predictions of TSP concentrations at short ranges.

Alternatively, smoke column behavior can be described by convection models that have been used to simulate the behavior of cumulus clouds (Roberts 1976). These models take into account the vertical variations in stability that occur in the atmosphere. This feature is especially useful since convective columns from forest fires may penetrate the top of the mixing layer and enter a region of more stable air aloft.

Atmospheric Transport and Dispersion

Meteorological factors which directly affect the transport and dispersion of the plume are wind speed and direction, depth of the mixing layer, and atmospheric stability. The USDA Forest Service Agriculture Handbook 360 entitled Fire Weather (Schroeder 1976) describes these concepts. The mixing layer is deeper in an unstable atmosphere and hence more dispersion will occur. Also, the more unstable the atmosphere is, the more rapidly dispersion will occur. Light winds will predominate in a stable atmosphere thus resulting in small dispersion of the plume. Wind speeds generally increase with height in the lower atmosphere. The plume will be transported at the wind speeds existing throughout the layer that it occupies. These winds will be stronger than the wind speed at the surface. Wind direction generally changes in a clockwise fashion with height. Therefore the entire plume may not travel in the same direction.

If the mixing depth is low due to a layer in the atmosphere, the smoke plume may be trapped below the stable layer, increasing adverse effects. If the convective column above a fire is strong enough to penetrate the stable layer, the smoke plume will rise through the inversion layer further downwind and provide more time for dispersion to occur. Figure 15 illustrates this condition.

Dell et al. (1970) reported on the general dispersion of smoke plumes from the Cascades when the Pacific Northwest was under the influence of

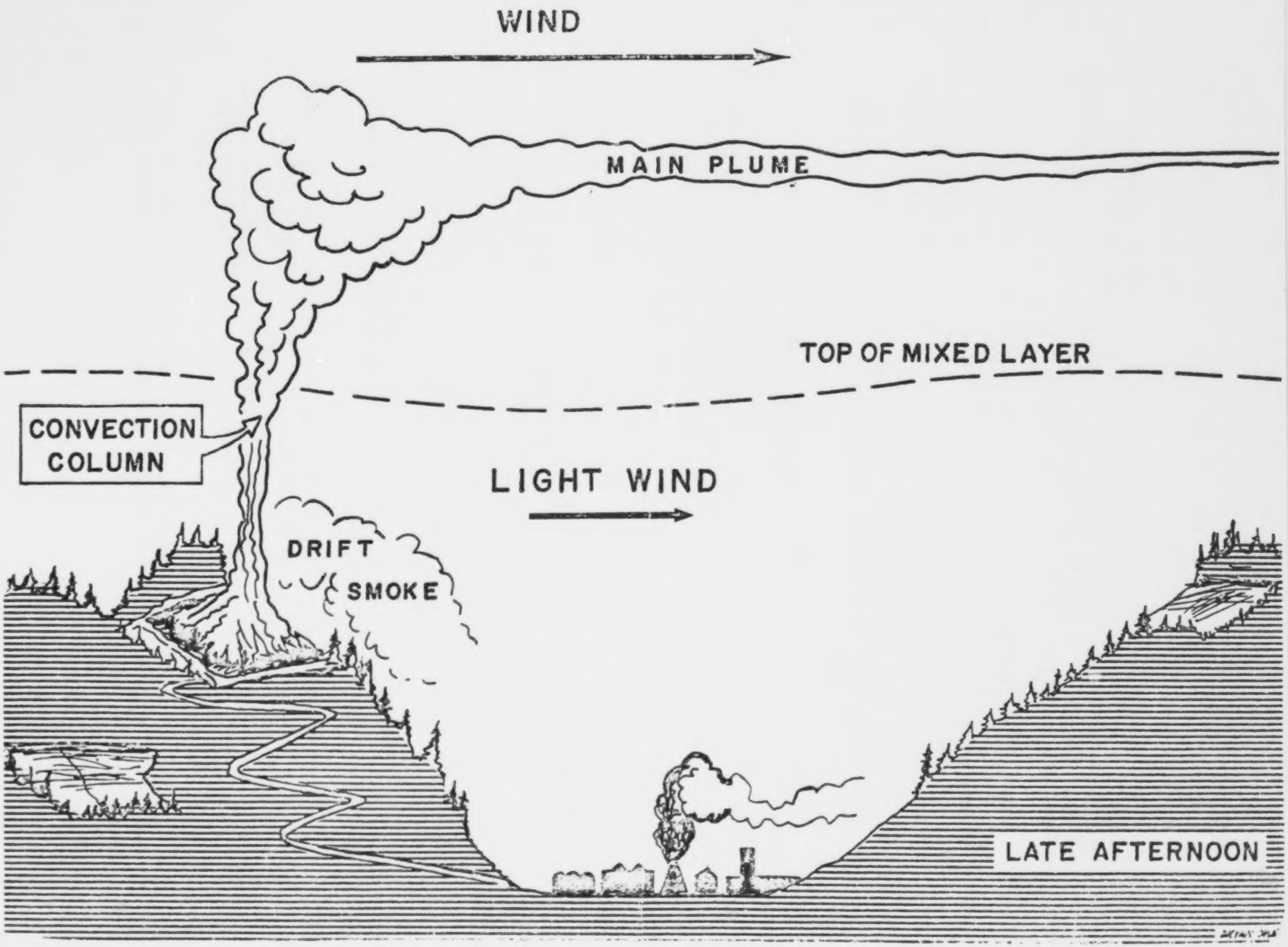

WIND
MAIN PLUME
TOP OF MIXED LAYER
CONVECTION COLUMN
LIGHT WIND
DRIFT SMOKE
LATE AFTERNOON

Figure 15. Plume penetrating through top of mixing layer. (Beaufait and Cramer 1969)

anticyclonic flow. Subsiding air in the high pressure system resulted in inversion layers between 300 and 400 m. Observed plumes from fires ignited above the inversion layer did not penetrate down through the inversion layers and did not enter the Willamette Valley.

The elevated inversion can occur during the daytime in the Willamette-Puget Trough region when cool maritime air is trapped at the surface by relatively warm subsiding air from a high pressure system. Studies which characterize fire intensity and plume rise versus depth of the mixing layer inversion strength are needed to refine these combinations of parameters for smoke management. A joint frequency distribution of stability classes with wind direction and wind speed is commonly used for air pollution modeling to calculate expected pollution levels. These frequency distributions are based on climatological records. Similar information modified to include the situations encountered in prescribed burning in complex terrain would provide desirable refinement to planning procedures. Probability forecasts of the occurrence of the most desirable conditions would aid in anticipating plume behavior. Climatic records are compiled by the National Climatic Center for all areas of the country. Seasonal variations as well as spatial variations in precipitation, cloud amount, soil moisture, etc. are determined from climatological records.

Local Influences on Dispersion

Dispersion of smoke plumes in the Northwest is influenced by the rough terrain and the proximity of the Pacific Ocean. Complex terrain causes a variety of local influences on air flow patterns such as up-slope and down-slope flow, mountain and valley winds, flow channeling, and mountain lee waves. Whether or not this type of phenomena occurs depends largely on the magnitude of the synoptic-scale flow. Strong large-scale winds can break up or prohibit local flows from forming.

Daytime solar heating and nighttime radiational cooling generate the driving force for mountain and valley flows and upslope and downslope winds. During the day the layer of air closest to the surface is strongly heated by the sun. As a result, this air rises and has an upslope component. Rising thermals of warm air exist above peaks and ridges. At night, radiational cooling produces a cold layer of air near the surface which flows toward the lowest elevations. If a smoke plume is entrained by this type of flow, smoke will accumulate in low-lying places. Similar effects occur in the up-valley and down-valley directions during the day and night respectively.

Channeling of airflow in mountain and valley systems was studied in eastern Tennessee by Nappo (1975). During stable conditions the topographic features affected the flow to elevations greater than 2000 m above the ground and to distances beyond 50 km. Mountain lee waves develop downwind of a mountain or ridge crest in a stable atmosphere with moderate to strong winds above the elevated terrain.

Turbulence is partly caused by the roughness of the surface over which air flows and is the primary mechanism for dispersion of smoke plumes. It is expected that dispersion will be enhanced in complex terrain, except when strong inversions are present in the valleys. Most field plume studies indicate that complex terrain contributes to alterations in air flow and to increased amounts of turbulent diffusion compared to those in flat terrain. Drainage flow and lee waves appear to be the flow characteristics most responsible for increased turbulent effects.

The maritime influence felt in the Pacific Northwest is due to the predominately westerly winds of the coastal sections. The maritime air that comes ashore is quite stable due to its fetch over the relatively cool ocean water. A stable layer near the surface of the water is transported inland. As the air passes over the Coast Ranges in the daytime, an unstable mixing layer develops, aided by the upslope winds due to solar heating. At night, radiational cooling produces a layer just above the surface which is more stable than the maritime layer. These phenomena are displayed in Figures 16 and 17.

With westerly synoptic-scale winds, the effects of a local sea-land breeze circulation cell developing in coastal areas due to differential heating of land and ocean would be masked by the larger-scale flow. When the onshore flow is weak there may be some potential for sea breeze cell development. Under strong insolation conditions land surfaces are heated more strongly than water surfaces, causing rising air over land which may flow out over the ocean where cooler air is subsiding. Cool air moves inland to complete the sea breeze circulation cell.

EVALUATION OF THE IMPACT OF FORESTRY BURNING

The impact of forestry burning can be assessed by several different approaches. Mathematical models have been developed to describe both the airflow and plume dispersion in forested complex terrain areas and to predict concentrations of pollutants downwind of fires. Pollutant concentrations of plumes have been measured at the surface and at upper levels. Tracer materials have been used to follow airflow patterns in forested areas. Pollutant measurements have been made in smoke-sensitive areas and these data have been both statistically and morphologically related to burning activity.

Modeling Studies

Despite the fact that several models have been developed to describe airflow in forested, complex terrain regions or predict pollutant concentrations resulting from forest fires, the available literature does not reveal any modeling studies that specifically determine the impact of slash burning activities on the smoke-sensitive regions of the Pacific

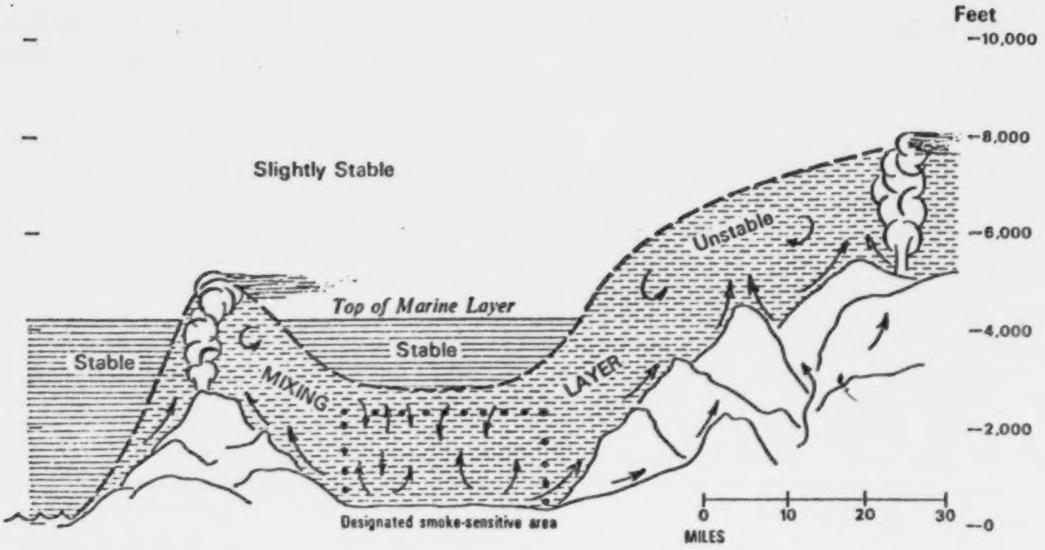

Feet
—10,000
—8,000
—6,000
—4,000
—2,000
—0
Slightly Stable
Unstable
Top of Marine Layer
Stable
Stable
MIXING
LAYER
Designated smoke-sensitive area
0
10
20
30
MILES

Figure 16. Common mesoscale and local afternoon dispersion conditions west of the Cascades during the warm season. The mixing layer is shallower in cooler seasons (Cramer 1974).

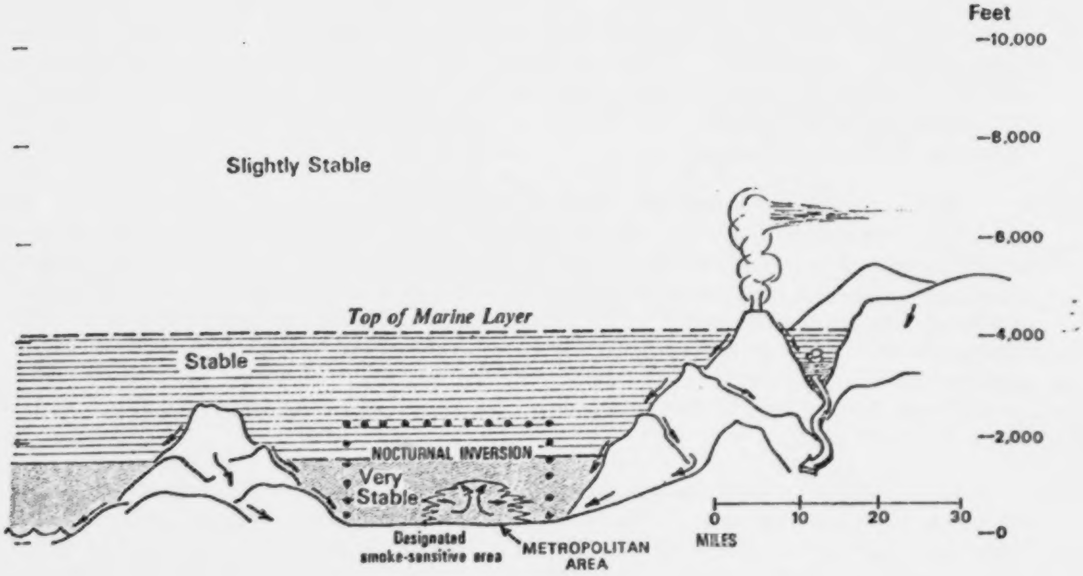

Feet
—10,000
—8,000
—6,000
—4,000
—2,000
—0
Slightly Stable
Top of Marine Layer
Stable
NOCTURNAL INVERSION
Very Stable
Designated smoke-sensitive area
METROPOLITAN AREA
0
10
20
30
MILES

Figure 17. Common nighttime or early morning condition during the warm season west of the Cascades. Downslope breezes develop on still, clear nights. Similar stratified conditions without downslope breezes may persist throughout the day during the colder seasons and during rainy weather (Cramer 1974).

Northwest. However, validation of such models is being pursued in Oregon and Washington. Modeling of airflow through the forest canopy is necessary to assess the impact of drift smoke.

Complex terrain airflow and dispersion models can be used to predict the pollutant concentrations that result from large smoke plumes of slash fires in Washington and Oregon. Researchers have developed numerical models to describe wind patterns applicable to the transport and dispersion of the already formed plume. Tang (1970) devised a mathematical model to determine airflow in and above a forest on horizontal and sloping terrains. Drag and vertical eddy exchanges were used to construct the models. The wind profile above flat terrain was basically concave upward in the trunk space, concave downward in the canopy, and logarithmically increasing above the canopy as shown in Figure 18. This basically agreed with observed data. The computed wind profile for sloping terrains contained a maximum above the canopy and in the trunk space as shown in Figure 19. The magnitude of the maximum wind depended on the slope of the terrain and the eddy exchange coefficient variation with height.

Kinerson and Fritschen (1973) used an analog computer to model three-dimensional coniferous forest density and determine airflow and dispersion of aerosols. Field studies performed by Fritschen et al. (1969, 1970, 1971) in an experimental forest in Washington were used to test the accuracy of the analog simulation. Satisfactory results were obtained with the model. It was concluded that wind direction, governed by vegetative distribution and density, was an important factor in determining lateral aerosol movement. Vertical motion of the aerosol was concluded to be primarily due to atmospheric stability. Kinerson and Fritschen (1971) also developed a model that specifically characterizes the canopy of a naturally regenerated Douglas-fir stand. The model validated satisfactorily when used to compute wind profiles.

Ryan (1977) developed a model to characterize surface winds in complex terrain, assuming that the winds resulted from vector addition of several independent wind components produced by mountainous terrain. The components include valley-mountain wind, slope drainage wind, land and sea breeze, synoptic-scale wind, and the channel effect of topography elements. The computed winds were comparable to observed winds in the San Bernadino Mountains of southern California. No reference was made indicating if Ryan's model has been adapted to compute dispersion of atmospheric pollutants in complex terrain.

Other models have been devised to characterize airflows and dispersion through complex terrain. Fosberg (1976a) developed a numerical model from the curl and divergence of the Navier-Stokes equation to determine the thermally driven wind pattern in mountainous terrain. The model evaluates the wind conditions and plume locations in remote areas. Data on the thermal field may be obtained by direct measurement or remote sensing. The

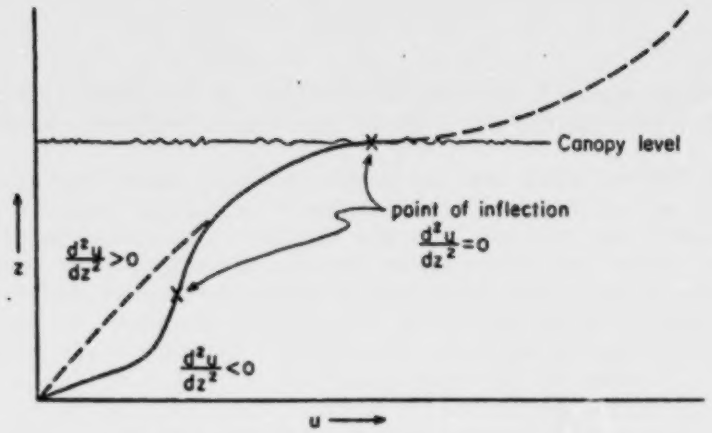


Figure 18. Wind profile of forest on flat terrain (z = height; u = wind speed) (Tang 1970).

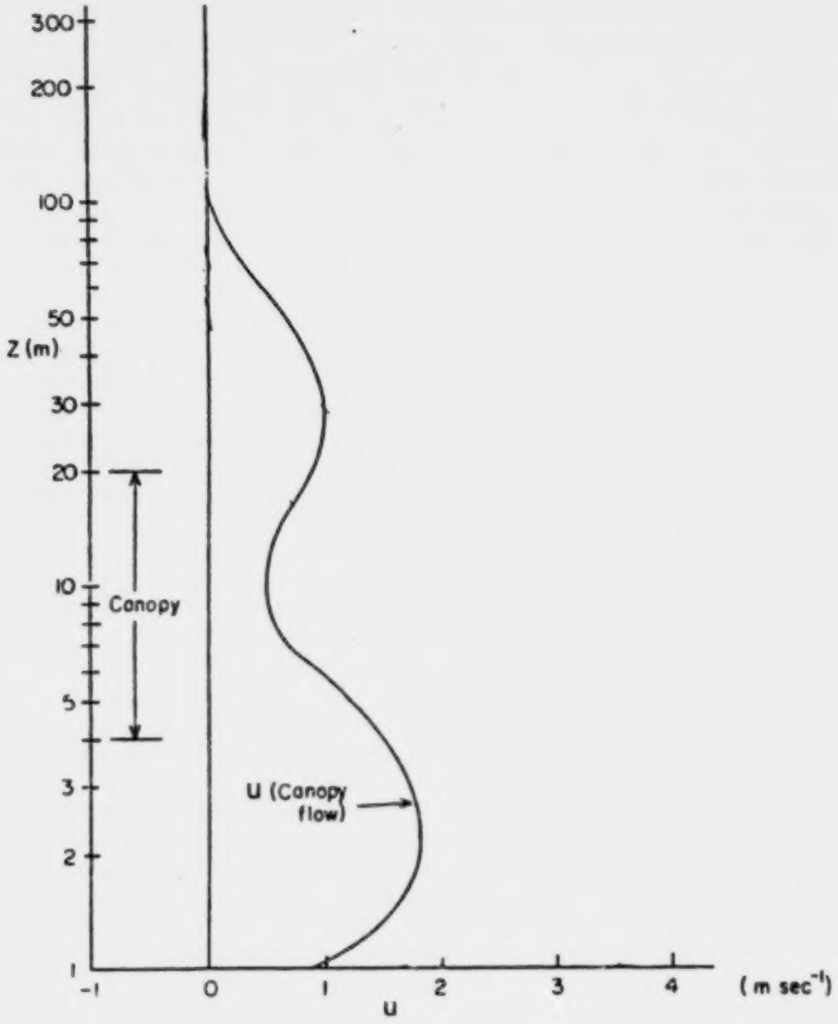


Figure 19. Wind profile of forest on sloping terrain (30°) (Tang 1970).

model was tested against observed conditions in California; errors of ± 1.1 ms^{-1} for wind speed and ± 20.7° for wind directions were documented.

Fosberg (1976b) also devised a single layer model for airflow and the dispersion of pollutants in the atmospheric boundary layer in complex terrain. The model was derived from the Navier-Stokes flow equation by neglecting advection terms and assuming an impulse solution. The model requires a minimum amount of data and describes a diagnostic model of the vector flow field. Six sets of wind data from the Oregon Cascades and one set from California were used to evaluate the model. The model validated reasonably well with a root-mean-square wind speed error of 2.0 ms^{-1} and a root-mean-square wind direction error of 1.9 points based on a 16-point compass. The Fosberg model is currently undergoing validation in the Willamette Valley region by the Oregon Air Resources Center at Oregon State University.

The LIRAQ model developed at Lawrence Livermore Laboratories is also being validated in the same region. The LIRAQ model has been previously evaluated by Environmental Research and Technology (Bass, Eschenroeder and Egan 1977). LIRAQ is a regional multiple-source air quality simulation model capable of predicting the dispersion of both nonreactive pollutants or reactive photochemical pollutants. The model produces spatial distributions of ground-level pollutant concentrations. Complex topographic effects on mixing height and local wind fields are included in the model. The impact of slash burning on air quality in any region near burning activity in the Coast Ranges or Cascades can be evaluated after the model has been validated.

Transport and diffusion models usually deal with point sources such as stacks. Adams et al. (1976) aerially monitored prescribed burns and concluded that long-range plume dispersal can be satisfactorily described with point source models. However, for short-range predictions, the length of the fire line must be considered. A line source model that predicts pollutant concentrations within 100 km of prescribed fires was developed for flat terrain in the South by Pharo, Lavdas and Bailey (1976). Both a "workbook" type model and a computer model (SMOGO) have been developed using Briggs' plume rise and the line source Gaussian dispersion equation of Turner (1970). According to preliminary reports by Lavdas (1978), the best results using the Briggs-Turner approach are obtained when 60 percent of the smoke can rise to the level predicted by the Briggs equations and 40 percent is dispersed from the ground level.

Williams (1974) used a different approach from the standard Gaussian plume formulation to estimate smoke concentrations from prescribed fires. Smoke concentration is expressed as a function of the smoke production rate and the volume change rate of the smoke plume. The plume is assumed to occupy a wedge rising from a line source with a quarter part of a right elliptical cone on either side of the wedge. The model was tested against measured data from two burns in Georgia. Predicted concentrations at distances of 805 m and 2415 m during a head-fire burn and 1610 m during a back-fire burn varied less than 25 percent from measured values.

Reiquam (1970) developed a mathematical model of an airshed that was evaluated for the Willamette Valley. Pollution concentrations are related to pollutant source distributions and intensities, and to the volume of air available for dispersion. The model describes the transport and accumulation of pollutants within an entire airshed during conditions associated with maximum observed concentrations. Calculated patterns of TSP concentration were qualitatively similar to patterns observed in the Willamette Valley during a period of field burning in late summer and early fall.

All of the models described in this section are applicable to the problem of describing and evaluating the transport and diffusion of smoke from prescribed fires in the Northwest. They differ, however, in both the techniques used to describe the transport and dispersal of smoke, and also in the scale for which they are meant to be applied.

Plume and Tracer Studies

Smoke plumes from prescribed fires have been observed by aircraft measurements in Washington, Oregon, Montana and Georgia. Dell et al. (1970) observed smoke transport from slash burns occurring above 2600 feet MSL in the Oregon Cascades during a 3-day period in October 1969. A stable layer of air below 10,000 feet existed during the period severely limiting mixing and causing pollution problems in the Willamette Valley. However, wind directions were such that smoke from the Cascades fires was carried eastward over smaller communities than exist in the more populated Willamette Valley. On the last day of the study, dense smoke was visible from the crest of the Cascades and eastward for 50 miles. Visibility at Redmond, Oregon, was decreased to 4 miles due to smoke from slash burns.

Radke et al. (1978) made airborne measurements of plumes from several prescribed fires in western Washington during October 1976. The particle number and volume distributions were measured for each fire, along with the light-scattering coefficient, CCN concentration, size spectra of cloud droplets, and concentrations of total gaseous sulfur, O_3, NO, NO_2 and NO_x. The plume from an 86-acre fire near Eatonville, Washington was observed to form a cumulus-type cloud 12 km across with a well-defined top at 1800 m. A plume measured 10 km downwind of a 49-acre fire near Centralia reached only 600 m. Some of the plume from the Eatonville fire reached the ground 13 km downwind, but the majority of the plume appeared to be above 900 m. CCN concentrations were approximately 5000 CCN/cm^3 and comparable to those reported by Eagan et al. (1974) for forest fire smoke. Although a majority of the particulate matter is organic and insoluble, 80 percent of the mass was in the 0.1 to 1.0 µm diameter range; this is large enough to be active for condensation despite the lack of soluble material. The mass concentration in the plume of the Eatonville fire was 250 µg/m^3 greater than the concentration in ambient air.

Air quality within a 60 km radius of prescribed burns in the Miller Creek and Newman Ridge areas of Montana was investigated by Adams, Koppe and Robinson (1967). Both aircraft and ground-based measurements were taken including hi-vol samples, visual range, CO and CO_2. The hi-vol TSP data determined that at three sites downwind from the fires, highly significent increases in TSP concentrations occurred on fire days as compared with nonfire days. Nephelometer measurements from aircraft were used to compute the standard deviations of concentration in the crosswind and in the vertical direction. Values of the scattering coefficient indicated particulate concentrations to be within the range of 90 to 230 $\mu g/m^3$, including a background of about 18 $\mu g/m^3$.

Murphy et al. (1976) reported aerially measured smoke dispersal from a 15 hectare controlled fire of forest debris in Georgia. Smoke density was measured by nephelometer, and the flight patterns were designed to yield data on the three-dimensional structure of the smoke plume. The smoke density profile did not seem to conform to a simple Gaussian model. High concentrations were found at low altitudes 1.6 km from the fire despite substantial plume rise in a buoyant column. It was hypothesized that smoke dispersion from a forest fire will vary depending on the stage of the fire's development.

Local atmospheric diffusion processes can be observed by releasing tracer materials into the atmosphere. Fritschen et al. (1969) released fluorescent particles and spores to determine mass and momentum transport at a forest border interface and to study dispersion into and within a forest canopy. Knowledge of such dispersion characteristics is essential for evaluating the impact of drift smoke. Fritschen observed that vegetation density strongly influences the wind speed profile in a forest. In the daytime, an inversion in the stem zone trapped the tracer while unstable conditions in the upper canopy and above the forest allowed rapid dispersal. At night, an inversion above the canopy trapped the aerosols within the forest.

Statistical Studies

The relationship of ambient pollutant concentrations to emissions and meteorological factors can be established by statistical techniques of correlation and regression. Multiple regression analysis can determine which variables have the greatest impact on air quality and determine the contributions of various sources to air quality.

Such a study has been conducted in the Eugene-Springfield, Oregon area (US EPA 1977). TSP data from three urban stations were available along with light-scattering, visibility and visual-smoke observations. Although the study was aimed primarily at assessing the impact of field burning, slash burning impact was also examined. Emissions data included the number of acres burned and the number of tons of slash burning conducted on a given day in each of four quadrants. Relevant meteorological data included daily average temperature, rainfall, relative humidity, wind direction and the number of days since precipitation had occurred.

During the 3-year Eugene-Springfield study (1974-1976), violations of both the annual and the 24-hour primary and secondary standards occurred. Results of the correlation and multiple-regression analyses showed that fugitive dust generated from other sources has a greater influence on ambient TSP and light-scattering measurements in Eugene-Springfield that does field or slash burning. Slash burning had a greater impact on visual-smoke observations than did field burning. Smoke observations were highly correlated with long periods of dry sunny weather. Field and slash burning equally influenced the visibility at the Eugene Airport.

The multiple regression equations predicted that the mean 24-hour contribution to TSP from field burning in the Eugene-Springfield area was 1 to 4 $\mu g/m^3$, while the maximum 24-hour contribution was from 13 to 43 $\mu g/m^3$. Slash burning was computed to contribute 3 to 15 $\mu g/m^3$ to the mean 24-hour TSP concentration, while the maximum contribution from slash burning was estimated between 21 and 84 $\mu g/m^3$. However, other areas of the Willamette Valley may experience greater smoke impact from burning activity than does Eugene-Springfield. Since burning generates large numbers of small particles (0.1 - 1.0 μm), it therefore is likely to have a greater impact on health and visibility. Legally, TSP measurements made with a hi-vol sampler are used to determine the impact of sources, but the public is more concerned with the health and visibility effects resulting from the small particles not measured with this method.

Dieterich (1971) reported on TSP data collected from central Georgia during a period of variable amounts of prescribed burning. A network of eight hi-vol samples was used. Based on seven days of data, the mean TSP concentration over the eight sites showed a correlation coefficient of +0.78 with the number of smoke plumes observed in the area during the day.

Filter Analyses

Microscopic analysis of hi-vol filters can be used to identify the impact of an emission source or group of sources based on TSP concentrations. The specific sources of particles can be identified by their size, shape, solubility, surface texture, transparency, and color.

Approximately 60 hi-vol filters from the Eugene-Springfield area underwent microscopy by McCrone Associates and the results were reported by US EPA (1977). An average of 8 $\mu g/m^3$ could be attributed to field burning with a range from 1 to 33 $\mu g/m^3$. Slash burning was determined to contribute 5 $\mu g/m^3$ on the average with the range of 1 to 15 $\mu g/m^3$. Total particulate readings for all sources averaged 101 $\mu g/m^3$* for this sample, with a range of 24 to 253 $\mu g/m^3$. Only optical microscopy which may not detect particles < 0.5 μm was used. Since a significant portion of smoke particles is < 0.5 μm, there is more uncertainty concerning the results. However, since most particles emitted from forestry burning are known to be less than 0.5 μm in diameter (see Table 11), these microscopic analyses do not give a true measure of the impact of forestry burning or particulate air quality.

RELATIVE EMISSIONS FROM FORESTRY BURNING

Normally, a rough indicator of the relative impact of a particular source category on regional air quality is the total emissions of that category in comparison to other source categories. However, this is a highly uncertain basis for assessing the impact of forestry burning, particularly in relation to the impact from wildfires. Burning conditions for prescribed fires can be selected to minimize the impact of emissions, but wildfires burn under various conditions, many of which result in severe degradation of air quality in populated areas. Wildfires are typically fast-moving headfires, which leave a major portion of available fuel to burn by smoldering. As discussed in Section 3, emissions of TSP, CO and HC are maximal in such a situation. Forestry burning consumes mainly dead fuel, but live fuels are included in wildfires. Burning live fuels, as simulated by including green leaves in laboratory test fires (Darley 1976), greatly increases emissions of TSP, CO and HC. Emission from wildfires would therefore be expected to be relatively greater than from prescribed fires, resulting in emission factors significantly higher than those listed previously in Table 8 for prescribed fires. For example, Ward et al. (1976) suggest average TSP emission factors of 50 pounds per ton for prescribed fires and 150 pounds per ton for wildfires. The concensus among experts actively engaged in forestry burning research is that emissions from wildfires, at best, are comparable to those from worst case prescribed fires. In the absence of wildfire emissions data, the upper values of the emission ranges listed in Table 8 probably represent the best conservative estimate of wildfire emission factors that can be made at the present time. These factors with substitution of the TSP factor of 150 pounds per ton, suggested by Ward et al. (1976) for the upper TSP value in Table 8, are:

CO:	500 pounds per ton
TSP:	150 pounds per ton
HC:	40 pounds per ton
NO_x:	6 pounds per ton.

---

* Of this TSP value, 17 percent was determined to be burned vegetable matter, including grass and wood. However, only 72 percent of this burned vegetable matter was determined to be specifically wood or grass. Hence it is likely that the figures cited in this paragraph are low estimates of the contributions of slash and field burning observed TSP values.

Emissions from forestry burning, wildfires, field burning, other types of open burning, and all other sources including industrial and automotive are summarized in Table 17 for the year 1975. The total emissions show that forestry burning and wildfires are major sources of TSP, HC and CO. However, the emissions from forestry burning are generally vented away from population centers, while those from wildfires can intrude into such centers at random. Hazard reduction to minimize occurrence and spread of wild fires is one objective of forestry burning, but the incidence of wildfires in the absence of such burning cannot be quantitatively determined. Statistics supplied by the State of Washington Department of Natural Resources (DNR) for the years 1973 through 1977 show the occurrence of 37 project wildfires which burned 19,345 acres. Forty-four percent of the project fires occurring on DNR-protected lands statewide started in unburned logging and thinning slash. An additional 20 percent of the fires were aided in their spread by burning through unburned slash. One fire stopped and was controlled at the point it encountered a previously prescribed burned area. In Western Washington, 14 of the 16 project fires started in and spread through unburned logging slash due to a variety of fire causes. These statistics raise a question relevant to assessment of the impact of forestry burning on air quality: Is there a trade-off between emissions from forestry burning and those from wildfires? That is, would the emissions from wildfires, due to more and larger fires, have been significantly increased during the period covered by the data in Table 17 if hazard reduction by forestry burning had not been practiced? The question cannot be answered quantitatively at this time, but the DNR statistics suggest that the trade-off is real and should be considered a major factor in assessing the relative impact of forestry burning on air quality. In considering this argument for the use of prescribed burning, one should bear in mind that there are alternative methods of hazard reduction, including prescribed burning. The pros and cons of these alternatives are discussed in Chapter 5.

SUMMARY

The previous section discussed in some detail a study conducted by US EPA (1977). This study was aimed at assessing the impact of field burning on observed TSP levels in the Eugene-Springfield area. Since slash burning was also considered to be a contributor to TSP concentrations, slash burning emissions were included in the study. The study concluded that the contributions of slash burning and field burning to measured TSP levels were significant. This conclusion was based on corroborative filter and statistical correlation analyses.

The study also suggested that the contributions of field and slash burning activities to fine particulate levels might be significant. These particles which are less than 0.5 μm in diameter are felt to impact most on health and visibility. Furthermore, the microscopic analysis carried out in the study was capable only of evaluating the characteristics of larger particles. The study concluded that field and slash burning were not principal factors in the nonattainment of national air quality standards which do not presently

TABLE 17. STATEWIDE EMISSIONS FOR OREGON AND WASHINGTON*†

Source Category/State	Total Suspended Particulates‡	Nitrogen Oxides	Hydrocarbons	Carbon Monoxide
Oregon:				
Forestry burnings §				
Low estimate	30,214	3,555	17,773	35,545
High estimate	119,077	10,664	71,091	888,634
Wildfires #	115,103	4,604	30,694	383,676
Field burning **	4,100	480	4,800	24,000
Other open burning	4,320	1,363	5,511	24,365
Other sources	93,614	194,421	276,564	1,084,731
Washington:				
Forestry burnings §				
Low estimate	22,530	2,650	13,253	26,507
High estimate	88,795	7,952	53,012	662,653
Wildfires #	34,068	1,363	9,085	113,559
Field burning **	2,200	200	2,600	13,000
Other open burning	5,464	1,082	9,213	49,088
Other sources	142,636	352,275	368,042	1,699,740
Oregon and Washington:				
Forestry burning §				
Low estimates	52,744	6,205	31,026	65,052
High estimates	207,872	18,616	124,013	1,551,287
Wildfires #	149,171	5,967	39,779	497,235
Field burnings **	6,300	680	7,400	37,000
Other open burning	9,784	2,445	14,724	73,453
Other sources	236,250	546,696	644,606	2,784,471

* Emission figures taken from National Emissions Report (1975): National Emissions Data System (NEDS) of the Aerometric and Emissions Reporting System (AEROS), U.S. EPA, April 1977, except as otherwise noted.

† Sulfur dioxide emissions are not included, since forestry burning does not emit significant sulfur dioxide.

‡ TSP emissions of this table do not include fugitive dust emissions due primarily to agricultural tilling (Oregon estimated at 156,776 tons during 1976).

§ Taken from Tables 9 and 10 of this report. Estimated tons of fuel burned are the basis for computed emissions and are subject to error. See page 43 for discussion of possible error.

# Wildfire tonnage figures are those used to estimate emissions for the National Emissions Report (1975).

** These estimates are taken from Source Assessment: Agricultural Open Burning, EPA-600/2-77-107a, July 1977, and correspond to the year 1973.

distinguish between fine and large particles. However, the study was unable to conclude that these sources did or did not have a significant impact on air quality or health. The study did indicate that slash burning had a greater impact on observed visibility measures than did field burning with the exception of one site where the contributions of the two sources were approximately equal.

Another study was recently completed by the Oregon DEQ and addressed the impact of field and slash burning using monitoring data from the entire Willamette Valley.[3] The study was based on a monitoring network with particulate samplers at seven locations in the Willamete Valley (Corvallis, Lebanon, Halsey, Junction City, Perrydale, Stayton, and Woodburn). The study was established primarily to evaluate the impact of field burning on air quality, but did not become operative until September 1977, when most field burning was complete. The monitoring network was used instead to monitor air quality during slash burning through October.

Monitoring data from the seven stations showed similar behavior and indicated that a single regional source of air pollution and/or poor atmospheric ventilation was responsible for observed particulate levels. Comparison of average particulate readings over the Willamette Valley with daily tonnages of slash burned in the counties of Clackamas, Multnomah, Lincoln, Tillamook, Marion, Polk, Yamhill, Benton, Lane, and Linn showed similar behavior. Statistical analysis of the data indicated a strong correlation between Valley-wide particulate readings, slash tonnages and atmospheric ventilation. A multiple correlation coefficient of 0.78 was obtained. Although the simple correlation between particulate readings and slash burning tonnages was not available in the DEQ report, inspection of graphs presented in this report do indicate a general correspondence between peaks in slash burning activity and highs in valley-wide particulate averages. The findings of this study correlate with the study by the US EPA, which indicated that slash burning contributes significantly to measured TSP levels in the Eugene-Springfield area.

---

[3] Field Burning Network Data Analysis--Preliminary Results, Oregon Department of Environmental Quality, 1978.

SECTION 5

METHODS OF REDUCING THE AIR QUALITY IMPACT OF FORESTRY BURNING

This section describes and evaluates methods of reducing the air quality impact of forestry burning. The first subsection describes current Smoke Management Programs, evaluates their success in minimizing air quality problems, and suggests improvements to these programs. The second section describes alternative burning techniques and their potential for reducing air quality impact. The final section describes alternative residue treatment techniques which do not require field burning of forest fuels and evaluates their potential for successful application.

SMOKE MANAGEMENT PROGRAMS--CURRENT PROGRAMS IN WASHINGTON AND OREGON[1]

Currently, both Washington and Oregon have Smoke Management Programs designed to limit the air quality impact of forestry burning activities. The Oregon Smoke Management Program was implemented in 1972[2] and is administered by the Oregon Department of Forestry in coordination with the Department of Environmental Quality. The Washington Smoke Management Program was implemented in 1971 and is administered by the Washington Department of Natural Resources in coordination with the Department of Ecology. Both programs were subsequently revised in 1975. The Smoke Management Programs represent a cooperative effort by the U.S. Forest Service, the U.S. Bureau of Land Management, the U.S. Bureau of Indian Affairs, private industry, state and local governments.

Description and Operation

The major features of each program are essentially the same. These features may be summarized as follows:

- The primary purpose of the program is to keep smoke from forestry burning out of designated areas. These designated areas are determined by the state's air pollution control agency and generally correspond to populated areas. Figure 20 shows designated areas for the two states.

---

[1] All of the information of this section is taken directly from the Smoke Management Programs of the Oregon DOF and the Washington DNR, except as noted otherwise.

[2] However, the precursor to Oregon's current Smoke Management Program was initiated by a memorandum of an agreement signed in 1969 by State, Federal and private fire control agencies and the Department of Environmental Quality.

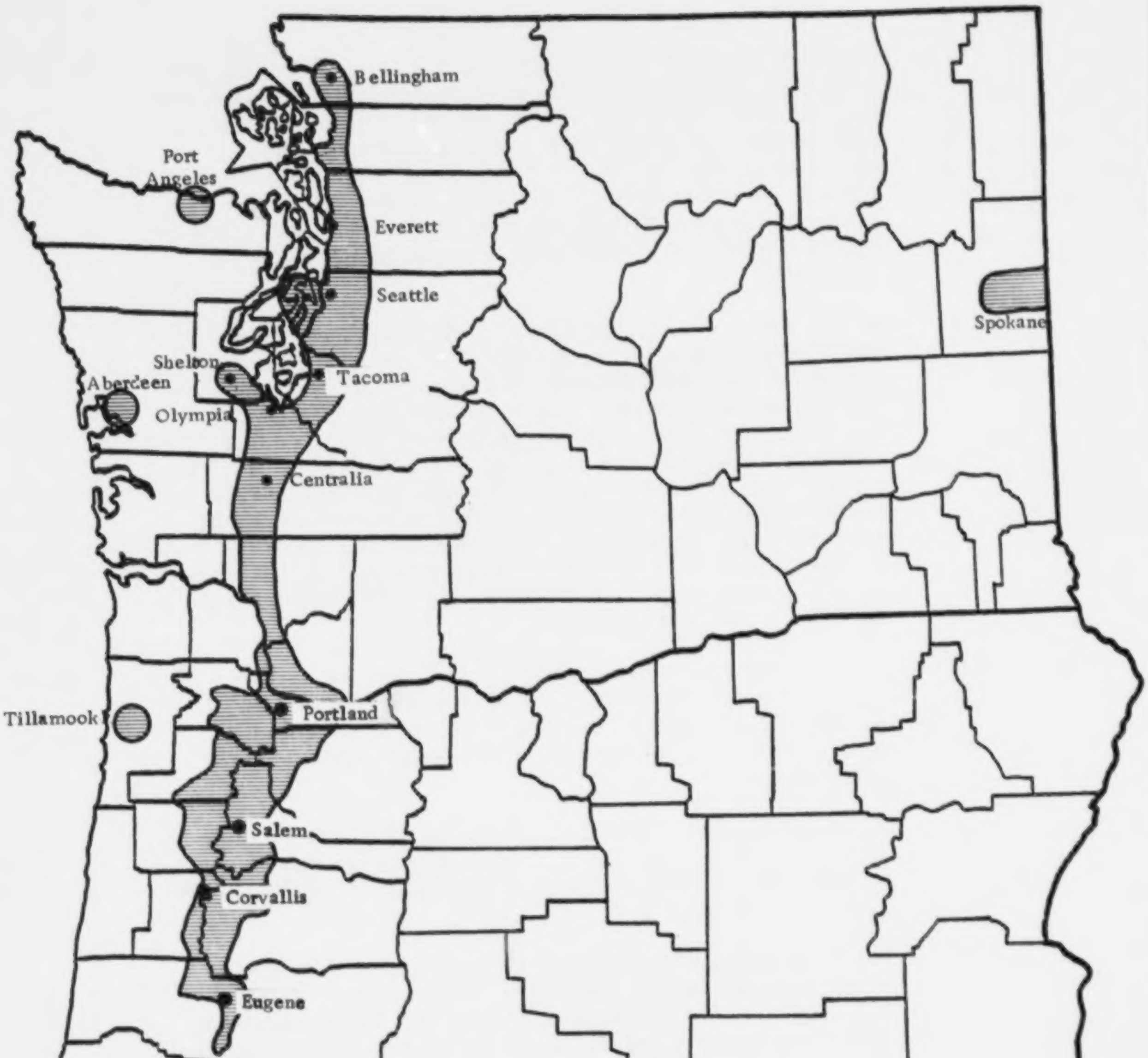

Bellingham
Port Angeles
Everett
Seattle
Spokane
Shelton
Aberdeen
Tacoma
Olympia
Centralia
Tillamook
Portland
Salem
Corvallis
Eugene
Coos Bay
Roseburg
Grants Pass
Medford
Ashland

Figure 20. Designated areas under Washington's and Oregon's Smoke Management Programs.

- Administration of the program is the responsibility of the State Forester. He closely coordinates his administration with the state air pollution control agency (DEQ or DOE) by curtailing burning activity when notified of air quality problems. In addition, he reports forestry burning activity to the state air pollution control agency on a daily basis. The state agency in turn notifies local air pollution control agencies.

- At the local level, the Smoke Management Program is administered by an Area Manager. It is the responsibility of the Area Manager to ensure that forestry burning activity within his area does not result in intrusions of smoke into designated areas. He also responds to directives from the State Forester to curtail burning activity in response to critical air quality problems. National Forests are considered as separate Management Areas, with the Forest Supervisor acting as the Area Manager. Within areas administered by the Bureau of Indian Affairs, the BIA Fire Control Officer is the Area Manager.

- A third level of administration takes place in the field. Field Administrators advise the burn operator in the preparation of burning plans and monitor the actual fire, in addition to issuing the permit to the operator.[3]

- Meteorological forecasts prepared by the Fire-Weather Forecast Offices of the U.S. Weather Bureau are relayed to the State Forester and to Area Managers at the beginning of each day.

- The Area Manager's decision to permit burns is determined by regulations published in the Smoke Management Plan, unless further restricted by the State Forester. These regulations relate total allowable fuel consumption within 150,000-acre areas to the elevation, proximity of designated areas, and meteorological conditions (Table 18).

---

[3] ITF/FSU, Final Report, 1977, p. 16.

TABLE 18. SUMMARY OF SMOKE MANAGEMENT PLAN RESTRICTIONS FOR WASHINGTON AND OREGON

	Distance to Nearest Downwind Designated Area	Maximum Daily Forestry Burning Permitted *	
		Oregon	Washington
Smoke vented toward designated area, below ceiling established for area	Less than 10 miles	No burning permitted	No burning permitted
	10 - 30 miles	1, 500 tons per 150, 000 acres	1, 500 tons per 150, 000 acres
	30 - 60 miles	3, 000 tons per 150, 000 acres	3, 000 tons per 150, 000 acres
	Greater than 60 miles	No restriction	Not specified
Smoke vented toward designated area, into deep mixing layer over area	Less than 10 miles	3, 000 tons per 150, 000 acres	3, 000 tons per 150, 000 acres
	10 - 30 miles	4, 500 tons per 150, 000 acres	4, 500 tons per 150, 000 acres
	30 - 60 miles	9, 000 tons per 150, 000 acres	9, 000 tons per 150, 000 acres
	Greater than 60 miles	No restriction	Not specified
Smoke vented toward designated area, above stable layer over area	Less than 10 miles	6, 000 tons per 150, 000 acres	6, 000 tons per 150, 000 acres
	10 - 30 miles	9, 000 tons per 150, 000 acres	9, 000 tons per 150, 000 acres
	30 - 60 miles	18, 000 tons per 150, 000 acres	18, 000 tons per 150, 000 acres
	Greater than 60 miles	No restriction	Not specified
Smoke vented away from designated areas	Not applicable	No restriction	No restriction
Smoke vented within designated area, but away from population center	Not applicable	Not specified	3, 000 tons per designated area
Smoke vented within designated area, toward population center	Not applicable	Not specified	100 tons per burn unit
Smoke vented above base of precipitating cloud	Not applicable	No restriction	No restriction

* In addition, Washington limits daily burning with 500, 000 acre units to 75, 000 tons of fuel.

- Information flow between the Area Manager and the State Forester is conducted by teletype. Information sent to the State Forester includes identification of future burns by location, size, etc., listings of burns planned for a given day, and accomplishment reports for the previous day's activities. At the end of the year, this information is summarized in an annual report prepared by the State Forester. This annual report and the individual burn data collected by the State Forester are the basis of the summaries of forestry burning activity presented in Section 2 of this report.

A major operational difference between the two programs is the computerized "Oregon Smoke Management System" that stores and retrieves information on planned and accomplished burns; currently Washington does not have such a system. The program in Oregon is limited to the area west of the Cascades and portions of Mt. Hood and Descutes National Forests east of the Cascades. The Washington program has jurisdiction over burning in the entire state.

In 1977, Oregon instituted a priority rating system which applies to the Willamette Valley area during the 60-day field burning period.[4] The purpose of this system is to reduce forestry burning activity during the field burning season by restricting burning permits to only those units which cannot be burned at other times. Burn units are assigned priority ratings of "high," "moderate," or "low" based on fuel characteristics, location, and silvicultural considerations. Normally, only "high" priority units are permitted to burn during this priority period.

The regulations which restrict burning activity are nearly identical for Washington and Oregon. They are formulated using the following key terms:

designated ceiling -- 2000 to 2500 feet above the average ground elevation for the designated area. For example, the designated ceiling for Spokane, Washington is 4000 feet

wind direction -- used to determine whether plume will flow toward or away from designated areas. Considered unknown if wind speed is less than 5 miles per hour

deep mixing layer -- a condition characterized by good atmospheric mixing from ground level to 1000 feet above designated ceiling stable layer -- an atmospheric layer which restricts upward and downward movement of air and by implication is not penetrated by a smoke plume unless the plume is released directly into the layer

---

[4] Oregon Department of Forestry Directive No. 1-1-3-200, July 15, 1977.

smoke vent height -- the height at which heat rise stops and plume motion levels off and is carried horizontally by the wind

distance to designated area -- the distance to the nearest designated area downwind of a planned burn.

These regulations may be summarized as follows:

1. If wind carries the smoke plume toward a designated area and smoke is vented to an elevation less than the designated ceiling for that area, severe restrictions are placed on burning activity. If the distance to the designated area is less than 10 miles, no burning is permitted; if 10 to 30 miles, up to 1500 tons of fuel may be ignited per 150,000 acres; if 30 to 60 miles, up to 3000 tons per 150,000 acres; if greater than 60 miles, no restrictions are applied.

2. If wind carries the plume toward a designated area and into a deep mixing layer, moderate restrictions are placed on burning activity. For example, if the distance to the designated area is less than 10 miles, up to 3000 tons of fuel may be ignited per 150,000 acres.

3. If wind carries the plume toward a designated area and vent height is greater than the height of the stable air layer covering the area and also above the designated ceiling for that area, slight restrictions apply to burning activity. For example, if the distance to the designated area is less than 10 miles, up to 6000 tons of fuel may be ignited per 150,000 acres.

4. If wind carries the plume away from designated areas, burning activity is not restricted, except as noted in item (8).

5. If smoke is vented into a precipitating cloud such that the smoke vent height is above the cloud base, no restriction is applied, except as noted in item (8). This condition is feasible only for pile burns.

6. In Washington, if the unit to be burned is located within a designated area and the wind carries the plume away from the population centers, a total of 3000 tons of fuel may be ignited per day within the designated area.[5]

7. In Washington, if the unit to be burned is located within a designated area and wind carries the plume toward the population centers, units with total fuel loading greater than 100 tons may not be ignited.[6]

8. In Washington, a maximum of 75,000 tons of fuel may be ignited per 500,000-acre unit, regardles of conditions. No such overall limitation is specified in the Oregon Smoke Management Plan.

Meteorological parameters are key to the regulation of burning activity. These meteorological parameters are provided by the fire weather meteorologists of the State Forestry Office and the National Weather Service. A key parameter in some of the regulations is smoke vent height. Although mathematical formulas do exist for evaluating vent height for a given planned burn, simpler guidelines are generally used in operation. These guidelines assume that an intense fire will normally penetrate a stable layer of air less than 1500 feet above the fire. That is, vent height may be assumed to be at least 1500 feet above ground level and burning may be permitted within the constraining regulations.

Effectiveness and Consistency

One measure of the effectiveness of the Smoke Management Program is the number of problem burns reported by the Oregon Smoke Management System. Problem burns are defined to be those which result in the intrusion of smoke into designated areas. Problem burns are usually determined by the field administrator who observes smoke traveling in the direction of a designated area. Problem burns are also detected by aerial observations which are broader in scope and hence more accurate than ground-level operations. Both techniques rely on visual observations.

In general, problem burns are caused by inaccurate meteorological predictions. The decision to burn a unit is based on parameters such as wind speed, direction and atmospheric stability. Inaccuracies in these data may result in an intrusion of smoke into a designated area. Inaccurate or untimely communications from the fire meteorological office to area managers is not a significant factor in causing problem burns. However, changes in meteorological conditions due to a normal statistical percentage of erroneous forecasts and inability to account for local terrain effects on meteorology are thought to be major causes of problem burns. Fewer problem burns are expected as meteorological forecasting becomes more accurate and its ability to account for local terrain effects increases.

---

[5] Regulations relating to burn units located within designated areas are not specified in the Oregon Smoke Management Plan.

[6] Ibid.

The percentage of problem burns reported by the Oregon Smoke Management System for the years 1975 through 1977 is very low (1.9 percent averaged over the period). The Washington SMP Annual Report for 1977 also reported a very low incidence of problem burns, with less than 1 percent of prescribed burns significantly impacting on designated areas.

Although the percentage of problem burns on an annual basis is low, monthly data in Oregon reveal periods of relative highs in percent of problem burn acreage. Table 19 gives the percent of problem burn acreage for each month for the years 1975 through 1977.

TABLE 19. PERCENT PROBLEM BURN ACREAGE BY MONTH FOR 1975 THROUGH 1977.

Month	1975	1976	1977
January	0	2.0	2.0
February	0	2.5	1.4
March	0	0	0
April	0	0	0
May	0.7	0.5	0.7
June	0	9.3	9.5
July	17.6	21.6	24.9
August	20.8	11.4	5.5
September	10.2	7.4	0
October	0.9	5.7	1.5
November	0.2	3.2	1.3
December	0	1.8	0.2
Annual	1.9	4.5	2.2

The table indicates that relatively high rates of problem burns occur primarily during the summer months. The cause of problem burns during the summer months may be due to meteorological conditions that are more difficult to anticipate from a smoke management standpoint; and inadequate weather forecasting for smoke management due to the priority of wildfire prevention activities. If the percentages of problem acreage occurring during the months of June through September were reduced to the levels observed during October and November (1.9 percent), the total problem acreage during the period 1975 through 1977 would have been reduced from 9055 to 5394 acres. The implication is that more effective management during the summer months would significantly improve the performance of the Smoke Management Program in Oregon.

The occurrence of problem burns is a limited measure of the effectiveness of the Smoke Management Program. Visual observations of problem burns during the daylight hours do not identify the possible impact of nighttime drift smoke. The concept of drift smoke and the mechanism by which it impacts on air quality are described earlier in this report. The impact of drift smoke on air quality depends on the presence of residual smoke at or near ground level and drainage winds to carry this smoke from the location of the burn to the valley floor. The occurrence of drainage wind in complex terrain with nighttime cooling is well established. Since drift smoke is primarily a nighttime phenomenon, an intrusion into a designated area would not be detected using current visual procedures. It is therefore possible that forestry burning is impacting on air quality within designated areas, despite the indications of recorded problem burns. At the current time, data are not available to substantiate or refute this impact.

A significant impact of forestry burning on air quality within designated areas is suggested by a study recently performed by the Oregon Department of Environmental Quality.[7] A correlation was found between slash burning activity in western Oregon and air quality measures collected during the fall of 1977. This study suggests that despite conscientious efforts of the Oregon Smoke Management Program personnel, forest burning smoke is entering designated areas, at least during the stagnant weather conditions of the fall. An extensive, followup study conducted by the DEQ in 1978 will attempt to better evaluate the impact of forestry burning activity on air quality in the Willamette Valley. A study of this type is needed to accurately evaluate the effectiveness of the Smoke Management Program in keeping forestry smoke from populated areas.

Foreseeable and Potential Improvements

There are several modifications which might be made to the Smoke Management Programs of Oregon and Washington to improve their effectiveness. As previously indicated, the two programs are almost identical from a regulatory standpoint. They are also similar from an operational standpoint, with the exception of the priority rating system used in Oregon during the field burning season. Some of the possible improvements which might be made to improve the effectiveness of the two programs are summarized as follows:

---

[7] 1977 Field Burning Network Data Analysis, Preliminary Results, Oregon DEQ, 1978.

1. Redefining designated areas
2. Making burning criteria area-specific, accounting for conditions which impact on air quality at different locations
3. Improving smoke management meteorological forecasts and extending the period of forecasting
4. Adopting regulations to minimize the effect of drift smoke.

In addition, it is apparent that little is known about the potential long-range impact of forestry burning. Smoke management is largely directed toward maintenance of air quality in urbanized areas in the general vicinity of burning activity. The potential of long-range effects should be investigated and smoke management practices modified as necessary to prevent long-range degradation of air quality due to forestry buring.

Designated areas have been defined to correspond to heavily populated areas, primarily in the Puget Trough in Washington and the Willamette Valley in Oregon. These should be periodically reviewed to ensure that changes in population distribution are reflected in designated area boundaries. In addition, it has been suggested that heavily utilized recreational areas--such as parks and wildlife areas--be considered "designated" during periods of heavy use. However, the addition of designated areas is likely to impose a considerable burden on the operation of the Smoke Management Program, as the number of allowable burning conditions is decreased. At present, Smoke Management permits, with few exceptions, burning in the Cascades when winds are persistent and from the west; burns in the Coast Ranges are permitted when winds are persistent and from the east. The establishment of parks and recreational areas, which dot both the Cascades and the Coast Ranges (see Figure 4), could greatly restrict and complicate smoke management. This factor should be carefully considered.

Various parts of the Northwest differ considerably in their ability to disperse pollutants into the atmosphere. The southern Willamette Valley has particularly poor dispersal conditions. As a result, air pollution episodes occur in the Eugene area. Witnesses before the Oregon Interim Task Force on Forest Slash Utilization have recommended that the Oregon Smoke Management Program be modified to specify different permissible burning conditions for different areas.[8] For example, it was recommended that the burning ceiling for the Medford area be increased to allow for better dispersal of pollutants in that area. Such a recommendation, if enacted, would probably result in better smoke dispersal. However, it would also decrease the amount of allowable burning activity, since there would be fewer days and fewer areas where burning would be permissible.

---

[8] Joint Interim Task Force on Forest Slash Utilization, September-November 1977, page 1.

The most critical parameters in effective Smoke Management decisions are meteorological. In particular, accurate data on wind speed, direction and stability conditions are key to the decision of whether and how much to burn. The majority of problem burns documented in the Oregon Smoke Management Systems are thought to be due to forecasts which did not reflect actual local meteorological conditions. Hence, improvement in smoke management can be expected with improvement in weather forecasting techniques. It is essential that the most timely and accurate forecasts are available to the area manager charged with burning activity within his area.

As indicated previously in this section, it is possible that drift smoke, carried by nighttime drainage winds, is intruding into designated areas, despite indications of problem burn tabulations to the contrary. Modifications can be made to the Smoke Management Program to minimize possible nighttime drainage effects.

Some possible modifications are:

- Stricter enforcement of mopup operations, to eliminate much of the drift smoke concentrations potentially contributing to smoke intrusion problems.
- Requirement for earlier conclusion at burning operations. This would give drift smoke time to disperse before nighttime drainage winds take effect.
- The prohibition of burns which, given combined meteorological and terrain conditions, are potential candidates for nighttime drainage effects.

ALTERNATIVE BURNING TECHNIQUES

Alternative burning techniques can be used to reduce the impact of forestry burning on air quality. This section evaluates the feasibility and potential impacts of extended burn periods, optimal burning techniques and new burning technology that may be used for slash disposal. Practical alternatives to underburning have not been documented and are not discussed in this document.

However, these alternative burning techniques, like the burning techniques presented in Section 1, may not be suitable for all prescribed burning applications. Highly variable meteorological factors and fuel and terrain conditions require site-by-site evaluations to determine the applicability of these alternatives. The alternatives presented here are primarily applicable to the West Side, where the removal of heavy accumulations of slash is a major forest management problem. Treatment of residue on the East Side is less problematic, since slash accumulations there are far less than on the West Side. Much of the burning conducted on the East Side is underburning and is carried out for silvicultural purposes.

Extended Burn Period

Present broadcast burning activities are concentrated within September and October when fuel conditions are optimal for ignition and the risk of spot fires in the surrounding forest is minimal. Smoke management regulations have further concentrated these activities into as few as 14 days in some areas for favorable smoke dispersion conditions.

Extending the burn period throughout the year would provide more flexibility for optimal smoke dispersion conditions and reduce emission concentrations expected during any one period.

The feasibility of utilizing alternate burn periods has been limited by seasonal meteorological conditions. Winter months are generally too wet and summer months too dry. However, conditions vary by site, suggesting that a site-by-site assessment is necessary to schedule the optimal time of burn.

The development of better fire ignition and control techniques and an increasing knowledge of fire behavior has allowed a limited but increasing amount of burning during the summer, winter and spring. Studies are in progress in the Pacific Northwest to compare the relative effectiveness of burning during different seasons.[9]

The winter burning season is the 5-month period from the beginning of November to the end of March. Winter pile burning techniques have been successful when the concentrated slash is covered with paper or plastic prior to the wet winter season. This technique is being increasingly utilized. The feasibility of winter broadcast burning has been limited due to the excessively wet slash fuel conditions that thwart present fire ignition techniques.

Winter broadcast burning may be technically feasible if scattered slash is treated with a protective petroleum or wax emulsion prior to winter rains. Feasibility studies have shown that the burnability of dry slash pretreated with the emulsions shown in Table 20 is increased as compared to untreated slash after as much as 8 to 10 inches of rain (Murphy et al. 1969, Schimke and Murphy 1966). However, these same emulsions have been found to inhibit the burning of green slash by preventing satisfactory drying (Schimke and Dougherty 1967). Emulsions have not been utilized because of cost constraints and air quality concerns over the emissions from burning these products.

---

[9] As cited in Steele and Beaufait 1969.

The potential damage of winter pile burning to soil and riparian vegetation is expected to be minimal because of the excessively wet conditions and small areas affected. On the other hand, the potential soil and water quality damage from a successfully ignited winter broadcast burn could be significant. Surface runoff from winter rains on large burn blocks cleared of slash and duff may be excessive, resulting in a greatly increased erosion potential. This is particularly true of the Coast Ranges, where winter rainfall levels may be as much as 15 inches per month.

TABLE 20. WATER REPELLENT SLASH COATINGS.

Asphalt Emulsions	Wax Emulsions
LAYKOLD Slow-set (ss-1)	Lumber Wax
LAYKOLD Rapid-set (ss-2)	Soil Sealant

The spring burning season is a 2-1/2-month period that starts after the winter rains in March and ends before the summer wildfire season in mid-June. Fuel conditions in late May and early June are generally satisfactory for broadcast burning. However, the effectiveness of a burn treatment earlier in the year will depend upon the residual winter moisture content of duff and slash fuels. Residual moisture may decrease the fire intensity, leaving partially consumed material and increasing relative atmospheric emissions. Spring burning may, however, reduce potential damage to soils and riparian vegetation when the moisture content of surface fuels obstructs complete consumption of the protective duff layer. Studies in experimental blocks of Douglas-fir logging slash averaging 64 tons/acre showed that spring burning consumed less than one-half the duff mantle consumed by fall burning (Steele and Beaufait 1969).

The summer burning season runs from mid-June to mid-September. The feasibility of broadcast and pile burning during the summer season has been limited by the wildfire hazard of excessively dry fuels. Broadcast burning has not been widely utilized during very dry periods except in low hazard, low elevation sites because of the excessive fire control precautions required by standard burning techniques to reduce the risk of spot fires. Concentrated pile burns are more easily controlled and may be more suitable for summer burning than broadcast burning.

Chemical fire retardents may be used to pretreat slash prior to summer burning to reduce normally expected high fire intensity. Broadcast or pile burn applications of diammonium phosphate (DAP) or ammonium sulfate (AS) have been found to substantially reduce fire intensity, the associated risks of soil damage and the risk of spot fires (Dodge and Davis 1966). Philpot et al. (1972) found very little particulate increase from burning AS-treated fuels; however, DAP significantly increased particulate emissions from treated fuels.

Potential environmental damage from summer burning may be significant. The high fire intensity and low duff moisture content associated with summer burning may result in greater soil and vegetation damage than is expected by burning at any other time of the year.

Optimal Burning Techniques

Burning techniques are available that can minimize the potential impact of forestry burning on air quality. These techniques optimize fuel arrangement and fire ignition for rapid and complete combustion.

Pretreatment by PUM or YUM techniques prior to burning can be used to remove larger fuel components which, if left to burn, produce intense heat and a prolonged residual smoldering fire. The density and size of the residual fuel components will depend on the degree of pre-burn YUM or PUM residue removal. Generally, YUM yarding removes material as small as 5 to 8 inches in diameter.

Fuels which are not piled must be sufficiently concentrated to burn efficiently. Residual fuel loading and scattered fuel continuity may not provide fuel concentrations and the needed fire intensity to minimize impacts on air quality.

Fewer larger burn blocks will not necessarily decrease visible smoke intrusions into populated areas as reported by the State of Oregon.[10] On the contrary (Table 21), the average sizes of problem broadcast burns reported in Oregon from 1975 to 1977 were consistantly and significantly larger than the average sizes of all the burns.

---

[10] Final Report, ITF-FSU, 1977.

TABLE 21. AVERAGE SIZE OF PROBLEM BROADCAST BURNS (Ac.)*

Year	Problem Burns	All Burns
1975	60.5	37.9
1976	59.3	36.9
1977	63.9	34.6

* From Smoke Management Plans, State of Oregon.

Pile burning provides more flexible burn scheduling during periods that are unsuitable for broadcast burning. PUM and YUM applications are presently limited by available equipment. Cable logging equipment is generally designed to handle larger material and is not cost efficient for piling small slash. Tractor piling is limited by slope and soil conditions as described in Section 1. Hand piling is not technically feasible due to the volume and size of residue materials to be treated.

Ignition and Mop-up--

Rapid ignition and mop-up techniques are expected to significantly reduce the emission problems generally associated with early cool-flaming and residual smoldering stages of a fire as described in Section 3.

Ignition techniques utilizing the helitorch or electrically detonated napalm devices described in Section 1 can provide rapid fuel ignition over an entire burn block. Under the right site conditions and fuel moisture and loading, potential soil damage is minimized and a fire of high intensity is created. Such high intensity fires have been shown to reduce undesirable emissions and to vent smoke through a high convective column, with desirable smoke management consequences (see Section 4). In addition, these fires are short in duration, generally lasting less than 2 hours.

Weyerhaeuser Company is presently testing an alternative helitorch system which will reduce the use of petroleum ignition fuels. Fuel capsules containing potassium permanganate are injected with ethylene glycol and water and dispersed. The water catalyst results in a delayed exothermic chemical reaction that is highly flammable. The economic and technical efficiency of this system should broaden the applications of this helitorch ignition system.

Complete fire mop-up activities started immediately after the flaming front of the burn has subsided will minimize residual smoldering. Standard techniques using water trucks and hand labor may be augmented if aerial tankers and chemical retardants are used on large burn blocks. The efficiency of mop-up activities will be significantly enhanced by pretreatment removal of larger slash materials which typically prolong the burn and are difficult to snuff out.

New Burning Technology

Research and development should be directed toward better onsite burning techniques that would eliminate the management and environmental impacts associated with open burning. These impacts include such components as smoke, residual charred logs, potential soil and watershed damage, fire hazard, the need for fire control manpower, fireline and mop-up activities, and a dependence on highly variable weather conditions.

Air Curtain Combustion--

Portable or trench air curtain burners are specifically designed for the combustion of wood waste with insignificant smoke emissions. However, this burning technique is not widely utilized at present because of extremely high operating costs (see Table 30, p. 145).

Rapid and complete combustion is encouraged by a blower system which directs an air curtain diagonally downward across the burner at a velocity of approximately 150 feet per second. Figure 21 shows the recirculated airflow pattern which results in a secondary combustion process of emissions. Combustion temperatures in this process range from 900 to 2300°F (Harrison 1978, McLean and Ward 1976).

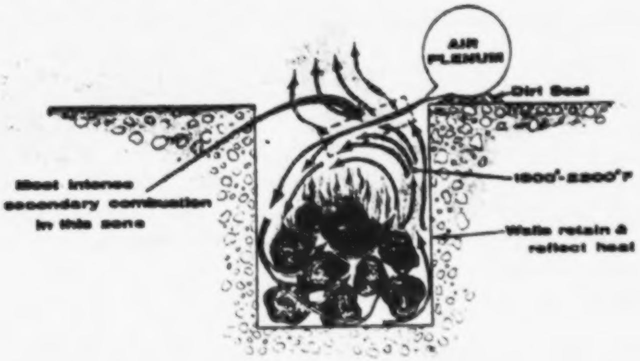

AIR PLENUM
Dirt Seal
1600°-2300°F
Most intense secondary combustion in this zone
Walls retain & reflect heat

Figure 21. Principle of air curtain combustion.

Air quality evaluations show that the air curtain combustion process will produce no visible smoke emissions if combustion temperatures are maintained over 1600°F (McLean and Ward 1976). Visible smoke approaching 20 percent opacity has been recorded during the 15 minute startup period. Golson (1975) found that breaking the air curtain by overloading the burner emitted smoke levels 70 to 80 percent less than would be expected from an open pile burn. The smoke disappeared within 60 feet, due to the superheated convection column.

The operating capacity of air curtain burners ranges from 5 to 25 tons per hour, as shown in Table 22. This production rate will vary due to fuel moisture content, although fuels with a moisture content as high as 200 percent have been consumed satisfactorily (Golson 1975). The satisfactory combustion of excessively wet fuels by an air curtain burner suggests its potential as a burning technique during the wet winter season.

TABLE 22. AIR CURTAIN BURNERS OPERATING CAPACITY

Type	Length (ft)	Capacity (tons/hr)	Reference
Camron PORTAPIT	20	6.2	Golson 1975
N/A	N/A	10	Murphy 1970
Camron ACCU	20	6.5	McLean and Ward 1976
N/A	N/A	10-15	Harrison 1975
DriAll Thermal Airblast	24	5-15	Harrison 1975
Incinerator	36	8-25	Harrison 1975
N/A	15	5	Geyer

Portable air burners are self-contained, trailer-mounted units which may be employed with YUM operations in areas of limited space or where accessible slash loads are relatively small but scattered. A ground trench system may be used for heavy slash disposal if enough flat terrain is available for the combustion trench and supporting equipment. The capacity of this system will increase with the length of the trench and is restricted only by the length of the available blower system. Complete slash disposal following burning is accomplished by refilling the trench with an earth cover.

Potential environmental damage from the air curtain burner is expected to be less than any other burning technique presently used. Soil disturbance on the treated site will depend upon the type of yarding technique utilized to pre-pile residues or deliver them within knuckle boom reach of the burner. A spot fire hazard may exist on windy days, due to glowing embers discharged when the air curtain is disrupted during loading operations.

Off-Site Incinerator--

Stationary off-site, high-volume incinerator equipment is available to dispose of logging residues and produce little or no atmospheric emission products. Although technically feasible, this alternative may not be cost-effective considering the mechanical handling and transportation requirements of processing this material to a fixed disposal point. Once out of the forest, the potential market that exists for this material would logically direct its utilization instead of disposal.

ALTERNATIVES TO FORESTRY BURNING

This section presents a general overview of the alternatives to forestry burning. The technical feasibility and potential environmental impacts of these alternatives are addressed and available cost data and an economic analysis of burning versus no-burn alternatives is presented.

The alternatives to forestry burning are shown in Figure 22. These alternatives include the use of mechanical or chemical treatments, improved harvesting systems, slash utilization, and no treatment. The practicality and desirability of these alternatives may not be generalized for the Pacific Northwest, hence any assessment of feasibility or silvicultural and environmental suitability should be made on a site-by-site basis.

Mechanical Treatment

Mechanical techniques for treating slash and for brushland conversion are technically feasible and versatile. These techniques do not eliminate slash materials, but may sufficiently rearrange and change the size and shape of the slash components to satisfy silvicultural and environmental considerations. Slash materials are mechanically treated by mastication, chipping, piling, scarification or burying.

Mastication--

Onsite crushing or shredding machines may be used to treat small diameter, concentrated slash. Materials less than 6 inches in diameter are reduced to a mat of wood chips and chunks. Larger material may not be broken up but will usually be compacted closer to the ground. This level of treatment is generally considered to be sufficient for silvicultural objectives, but may not significantly reduce wildfire hazard.

The tractor support needed by these devices restricts their use to terrain with slopes less than 30 percent. Present applications have been limited to small thinning slash and brushland conversion. Applications in heavy logging slash may be feasible in conjunction with the utilization or piling of large material.

Chipping--

Onsite chipping may be used to treat small concentrations of slash or in conjunction with PUM or YUM operations. Small mobile or tractor-mounted chippers are adequate to treat small volumes of concentrated slash materials up to 6 inches in diameter, but are limited to terrains of less than 30 percent slope. Larger materials require PUM or YUM support operations in

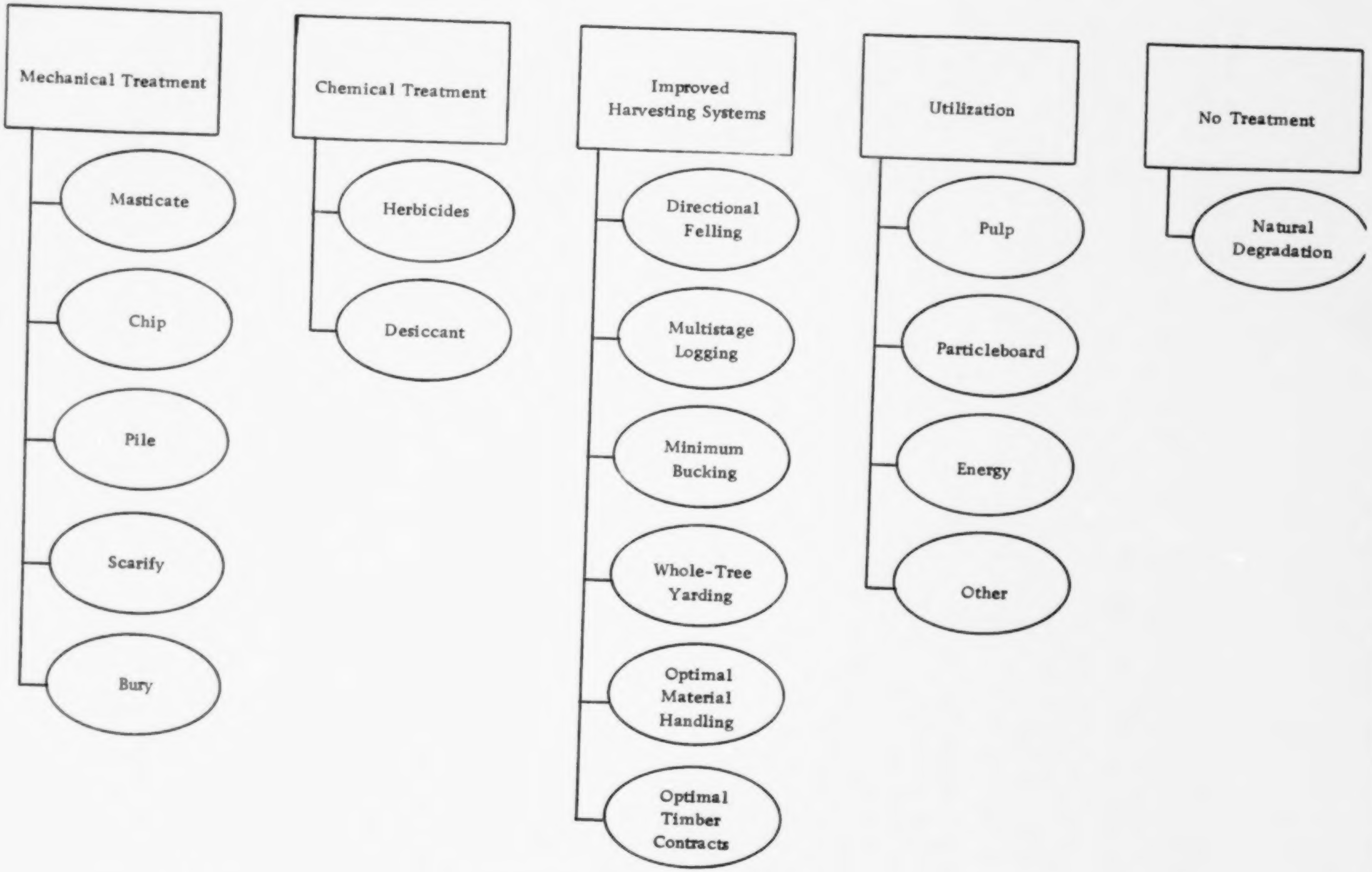

Mechanical Treatment
Masticate
Chip
Pile
Scarify
Bury
Chemical Treatment
Herbicides
Desiccant
Improved Harvesting Systems
Directional Felling
Multistage Logging
Minimum Bucking
Whole-Tree Yarding
Optimal Material Handling
Optimal Timber Contracts
Utilization
Pulp
Particleboard
Energy
Other
No Treatment
Natural Degradation

Figure 22. Alternatives to forestry burning.

conjunction with larger timber processor-type chippers that are limited to roadside or landing operations. Present slash chipping operations are limited to roadside treatments of thinning slash. However, onsite chipping applications are expected to increase in conjunction with increasing slash fiber utilization (see Utilization presented later in this section).

Piling--

YUM and PUM techniques as described in earlier sections may be used to pile or windrow slash without further treatment. Piling operations can sufficiently break up the continuity of slash concentrations for regeneration planting and reduced fire hazard. Piling operations concentrate and increase the accessibility of slash material and thus enhance the potential for more complete utilization.

Scarification--

Ground scarification techniques expose mineral soil for regeneration planting and break up the continuity of slash fuels to reduce fire hazard. Tractor scarification is limited by terrain and soil conditions. Recently developed cable and High Lead Scarification (HLS) techniques have been successfully used in brush and slash areas not feasibly treated by tractor (Ward and Russel 1975). Scarification techniques are used in conjunction with piling or windrowing to better satisfy silvicultural considerations.

Burying--

Field studies indicate that burying slash is technically feasible (Schimke and Dougherty 1966, Harrison 1975). Onsite pits can accommodate most piled or tractor-scarified materials. Large slash components and heavy material concentrations are difficult to treat. Necessary tractor support limits this technique to relatively flat rockless terrain.

Potential short- and long-range environmental effects may be of concern. Burial sites may not support trees until slash materials are decomposed. There are indications that wood decay is inhibited under anaerobic burial conditions (Evans 1973). These anaerobic conditions may also produce wood leachate pollutants. Volatile organic acids may be leached into ground waters (Sweet and Fetrow 1975). Under reducing conditions, these acids may further degrade water quality by dissociating heavy metals from the soil substratum.

These techniques can be used in combinations to achieve desired treatment levels. YUM yarding alone may not provide adequate logging residue treatment. Present specifications leave materials less than 5 to 8 inches in diameter on the site, impeding regeneration efforts and maintaining a temporary fire hazard until degraded. Competing vegetation to seedlings is not deterred and often requires additional treatment.

The onsite feasibility of the various mechanical techniques are dependent on the capabilities of available machines. Table 23 describes the limitations of the various machines presently used to treat slash. Prototype equipment for slash treatment is constantly being developed by private industries and at the San Dimas, California and Missoula, Montana equipment development centers of the U.S. Forest Service.

TABLE 23. MECHANICAL SLASH TREATMENT TECHNIQUES

		Size Limitation				
Equipment or Method	Slope Limitation (%)	Diameter (in)	Length (ft)	Support Equipment Needed	Disadvantages	Advantages
Masticate						
Tractor crushing	30	4-6	None	None	Very Inefficient	OK in small material
Youg Tomahawk & ATECO Compactor				Tractor, D6 or larger	Slow - needs hard ground and brittle material	Good, results with small, dry material
Towed Rolling Choppers	15-20	4-8	None	Tractor, D6 or larger	Sensitive to rocks - blades break; damages desirable tree seedlings	Good results with small-stem material
National Hydro-Ax	30	4	None	None	Leaves stubble which can resprout	Thorough treatment
Kershaw Klear-way	25	6	None	None	Leaves sharp stubble which can resprout	Thorough treatment
Trakmac/ Trailmaker	35	18	None	None	Undependable	Low ground compactor
Tree Eater	20	10	None	None	Undependable; damages desirable seedlings	Good results
Chip						
Nicholson Ecolo Chipper	Limit of yarding method	24	None	Grapple skidder	Large initial investment	High quality job
Vermeer 671	Limit of yarding	24	8	Loader	Limited to short material	Good results with short material
Roy Ecological Demolisher	Limit of yarding method	96	25	Crane	Large initial investment	High quality job
Pile						
PUM	30	None	15	Tractor, D6 or larger	Potential soil compaction	Low cost

(continued)

TABLE 23. (continued)

Equipment or Method	Limitation (%)	Size Limitation Diameter (in)	Size Limitation Length (ft)	Support Equipment Needed	Disadvantages	Advantages
Pile						
YUM	Limit of yarding method	None	15	Cable Yarder	Inadequate treatment of small materials	Minimal environmental effects
Hand	60	4-8	5-10	None	Slow, limited to small material	Minimal environmental impacts
Scarify						
Tractor	30	None	None	None	Potential soil compaction	Good results
Cable (HLS)	None	12	None	Cable Yarder	Potential soil erosion	Good results in small material
Bury						
Tractor	15	None	10	None	Slow, ground settling	Aesthetically appealing

The environmental effects of mechanical slash treatments are dependent on the degree of site disturbance that occurs as a result of soil scarification and damage to residual vegetation. Site disturbance may be no more than expected from logging operations or may accelerate deterioration of previously logged areas by further disruption of surface vegetation.

Soil damaging effects have been recognized and are regulated by State forest practices regulations. Erosion or compaction will vary, depending on soil conditions, terrain, and the extent of surface scarification. Techniques that leave a mat of residual woodchips on the soil surface will minimize soil disturbance.

Residual slash alters soil water distribution and obstructs drainage channels (Swanston 1974). Chip material washed into streams may physically disrupts fish habits (Ruth 1975). The potential toxicity of the leachates from this type of material has not been well substantiated although there is indirect evidence that the leachates are toxic to fish (Evans 1973).

Chemical Treatment

Chemical herbicides can be used for temporary control of undesirable vegetation. Forestry applications have been effective for brushland conversions, conifer thinnings and conifer release treatments. Available formulations and application methods provide versatile options for forest management and environmental considerations (Table 24).

Broad spectrum formulations are used in brushland conversion for preparation of seedling sites. Aerial application allows efficient treatment of terrain not feasible by other methods. Slow-release granular formulations and the synergistic effects of two or more herbicide combinations provide an effective means of controlling a variety of undesirable trees, shrubs or grasses (Gratkowski 1974).[11]

Selective herbicide formulations and/or application methods are used to control specific plants without injuring others. Selective herbicides are used in conifer release treatments to control competing hardwoods and grasses without affecting desirable conifer seedlings. On the other hand, conifer thinning treatments use selective application methods that allow treatment of individual trees. Selective application methods are usually accomplished by hand spraying or direct tree injection of the herbicide.

Chemical herbicides provide at best only partial treatment of slash. Vegetation control is temporary, usually less than 2 to 3 years,[12] and does not reduce slash concentrations.

---

[11] As cited in Cramer 1974.

[12] Personal communication, E. Feddern, Publishers Time Mirror, Inc., October 11, 1977.

TABLE 24. PROPERTIES OF HERBICIDES USED FOR FOREST VEGETATIVE CONTROL

Herbicide	Formulation	Application Method	Application* Rate	Use Selectivity	Half-life Persistence
AECP (Ammonium ethyl carbamoyl-phosphonate	Krenite-water soluble liquid	Aerial ground	1-1/2 to 3 gal/A	Deciduous species for site preparation	<4 mo.
Amitrole-T	Amino triazole + ammonium thio-cyanate liquid	Aerial ground	1/2 to 1 gal/A	Salmonberry and elder-berry; will damage Douglas-fir if applied too early or too late	<4 mo.
Atrazine	80% wettable powder	Aerial ground	3 to 4 lb ai/A	Annual grasses and some forbs; does not damage conifers	<4 mo.
Dalapon	74% sodium and magnesium salts-water soluble	Aerial ground	3 to 11 lb ai/A	Annual and perennial grasses for site prepa-ration; use with atrazine or directed sprays for release	<4 mo.
Dicamba	Dimethylamine salt	Injection	Undiluted or 1:4 in water	Hardwoods and conifers	5 to 8 mo.
	Dimethylamine salts of dicamba & 2, 4-D or 2, 4, 5-T	Aerial ground	1 to 3 gal/A	Shrubs and weed trees for site preparation	5 to 8 mo.
	Oil-soluble acid of dicamba + isoactyl esters of 2, 4-D or 2, 4, 5-T	Aerial ground	1 gal/A	Shrubs and weed trees for site preparation	5 to 8 mo.

* ai = active ingredient

(continued)

TABLE 24. (contimued)

Herbicide	Formulation	Application Method	Application Rate	Use Selectivity	Half-life Persistence
MSMA	Monosodium acid methanearsonate-water soluble	Injection	Undiluted	Hardwoods and conifers	<4 mo.
Picloram	Potassium salt + invert emulsions of 2, 4-D or 2, 4, 5-T	Aerial ground	1 to 4 quarts picloram + 1 to 4 gal of phenoxy invert	Shrubs and week trees for site preparation	8 to 12 mo.
	Trilsopropanolamine salts of picloram & 2, 4-D (Tordon 101R and Tordon 101)	Injection	Undiltued	Hardwoods and conifers	8 to 12 mo.
	Trilsopropanolamine salts of picloram & 2, 4-D (Tordon 101) with or without low volatile esters of 2, 4, 5-T or silvex	Aerial ground	1 to 4 gal/A	Shrubs and weed trees for site preparation	8 to 12 mo.
	Isooctyl ester of picloram + PGBE ester of 2, 4, 5-T (Tordon 155)	Aerial ground	1/2 to 1 gal/A	Shrubs and week trees for site preparation	8 to 12 mo.
Silvex	Low-volatile esters (BOE, PGBE)	Aerial ground	1/4 to 2/4 gal/A	Shrubs, weed trees and forbs; damaging to conifers	5 to 8 mo.

(continued)

TABLE 24. (continued)

Herbicide	Formulation	Application Method	Application Rate	Use Selectivity	Half-life Persistence
2, 4-D	Amine	Injection	Undiluted or 1:1 with water	Hardwoods except cherry and bigleaf maple	<4 mo.
	Low-volatile esters (Isooctyl, BOE, PGBE)	Aerial ground	1/4 to 3/4 gal/A	Shrubs, weed trees, and forbs; for site preparation and conifer release (except pines)	<4 mo.
2, 4, 5-T	Low-volatile esters (Isooctyl, BOE, PGBE)	Aerial ground	1/4 to 3/4 gal/A	Shrubs, weed trees, and forbs for site preparation and release	<4 mo.
	Amine	Injection	Undiluted or 1:1 with water	Hardwoods	<4 mo.

The feasibility of accelerating slash decomposition using chemical sprays has been studied in the Pacific Northwest (Ward 1975). Results indicate that the spray application of ammonium phosphate, urea, asparagin, 2,4-D and 2,4,5-T, or a plastic moisture barrier will not accelerate wood decay.

Herbicides used in combination with mechanical alternatives are more effective in slash treatment and can reduce the soil disturbance and other environmental effects associated with mechanical techniques. Two to three periodic herbicide appications are usually required after mechanical site preparation to ensure the establishment of new conifer seedlings.[13]

Adverse environmental effects depend on the persistence, accumulation and toxicity of a particular herbicide formulation. The herbicides that are presently registered by EPA for use in forest management have been observed to insignificantly affect wild life, soil microorganisms, water quality or air quality.[14] Damage to desirable vegetation is probable when broad spectrum formulations or application methods are used. Damage to riparian vegetation may result from aerial drifting of herbicides applied by plane or helicopter. However, improved spray nozzles and the use of low volatile formulations are expected to minimize this potential impact.[15]

Improved Harvesting Systems

Present harvesting systems generate considerably more logging residues than can be utilized. Logging residues may be significantly reduced by harvesting systems directed towards maximum utilization. The optimum system would only cut what could be utilized or rapidly treated. Of course, the successful application of any harvesting system that generates more usable wood fiber is dependent upon the market demand for this material. Market conditions that do not encouragae slash material recovery, necessitate some type of disposal activity. Thus, improved harvesting systems must provide an economic incentive along with technical feasibility for increased slash utilization.

Research and development of improved harvesting systems are ongoing in the Pacific Northwest under a cooperative effort by the USDA Forest Service and forest industries (Clarke 1972, USDA FS 1974).

The environmental effects of improved harvesting systems may be no more than expected from present logging operations. Removal of larger quantities of slash materials is not expected to affect the nutrient budget of most soils in this region although specific sites which are nutrient deficient or have fragile soils may be adversely affected. Helicopter logging techniques have been successfully used to minimize site disturbance during logging activities and to yard material when other techniques are not feasible. However, the low operating efficiency and weight limitations of helicopters currently limit their application to high grade saw logs.

---

[13] Personal communication, E. Feddern, Publishers Time Mirror, Inc., October 11, 1977.

[14] Unpublished E. I. S. on Herbicides in PNW Forests, USDA FS.

[15] Personal communication, M. Newton, Oregon State University, February 21, 1978.

Directional Felling--

Uphill or directional felling in old-growth stands can help minimize logging slash by reducing log breakage and thus increasing potential utilization as high-grade material. Directional control is accomplished with the aid of cables or hydraulic jacks. Although these control methods may increase logging costs by two to three times, field applications by forest industries indicate that these costs are easily offset by greater log recovery and utility (Burwell 1977). Gross volume recovery may be increased as much as 30 percent depending on terrain conditions (ITF-FSU 11/17/77).

Multistage Logging--

A two-stage logging operation can recover low-grade material that would at present remain as slash. Normal logging operations would be preceeded or followed by light-material handling systems to recover small-diameter material. Prelogging increases the utility of small material usually damaged during normal logging operations. Prelogging also lessens timber breakage during normal felling and yarding operations. Post logging salvages small logging residue from normal logging operations.

Minimum Bucking--

Minimizing preyard bucking of logs into uniform length classes optimizes the utility of low-grade materials. Shattered log ends and extraneous log lengths that are bucked prior to yarding are not easily handled by standard yarding machines so they remain on the site as slash. Minimum bucking encourages the yarding and processing of this material for utilization.

Whole-tree yarding--

Whole-tree yarding may be used to eliminate the need for any bucking. Applications have been limited by yarding capabilities and the present utility of whole tree fiber materials in the Pacific Northwest, although this process is commonly used in the Southeast by Weyerhaeuser Company and other forest industries. (See Utilization presented later in this section.) Also, the limited area of log landings may facilitate slash disposal piles contiguous with log yarding activities.

Optimal Material Handing Techniques--

More efficient logging machinery can improve opportunities for slash utilization. Prototype systems are being developed to yard, preprocess and transport slash materials. Lightweight cable-yarders provide more material-handling versatility, greater mobility and more rapid in-haul capabilities.

Mobile chippers and tree processors reduce irregular slash components to uniform chip material that can be efficiently loaded and transported for utilization.

Optimal Timber Contracts--

The contractual requirements of timber sales on public lands may be used to promote better logging slash utilization. Lump sum or per acre pricing (PAM) of small materials encourages efficient logging techniques and maximum utilization by an operator. PAM has been shown to significantly increase residue utilization as compared to traditional per-thousand board feet pricing (PM) (Pierovich and Smith 1973).[16]

The introduction of sustained yield unit agreements have been suggested as a method to improve utilization (U.S. General Accounting Office 1973). Guaranteeing a long-term timber supply would encourage development of local processing facilities for low-grade material.

Salvage rights and subsidies for residue removal may be used when market conditions will not support the sale of subgrade material. The desirability of cleaning up slash materials may justify some form of purchaser credit.

On a smaller scale, free-use firewood permits encourage individual removal of slash. However, this nonsystematic hand technique is limited to roadsides and is at best a partial alternative.

Utilization

Increased slash utilization can reduce the need for further slash treatment. Total tree utilization standards outside of the Pacific Northwest have been shown to reduce wildfire potential to a level requiring no further fuel modifications (Brown 1974). Silvicultural objectives for burning slash may be partially met by removing slash for utilization. In the case of pile burning, removing the piles rather than burning them will accomplish silvicultural objectives.

Slash utilization would, in general, have little adverse effect on soils, vegetation or wildlife (Sandberg 1977).[17] However, slash removal may have detrimental effects in isolated situations when: tree seedling survival depends on the shade of residual slash, erosion of steep, unstable slopes is prevented by slash and vegetative cover, and surface erosion is increased on steep, unstable slopes without slash or vegetative cover, or the habitats for local wildlife populations are provided by slash.

---

[16] No significant difference in PAM and PM residue loads was found by Hamilton (1975).

[17] ITF/FSU. Exhibit A. November 7, 1977.

The use of slash material is dependent on the capability and efficiency of the forest industries to process low-grade fiber that may contain undesirable species, rot, defects, rock and dirt. Fougler (1976) suggests that materials less than 4 inches in diameter can not be efficiently utilized by present processes.

The material handling and production alternatives that are available for slash utilization are characterized in this section. Market influences are discussed as is necessary to clarify the economic feasibility of these alternatives.

Material Handling--

The value of slash as a raw material for wood products or energy depends largely upon the efficiency of material handling and processing as described by Adams (1976). These processes must be efficient enough to allow slash materials to compete with mill residues and other sources of raw material; presently, this is not the case. The cost of delivering slash material is as much as 10 times that of mill residues where handling costs are absorbed by the primary wood products (Grantham 1974). Slash utilization depends on the availability and application of preprocessing and transportation systems that can efficiently handle this material.

A computer simulation model has been developed by the USDA-FS that can be used to assess different slash material handling systems (Bare 1976). The model traces the flow of materials through pre-specified combinations of processing and transporting operations to evaluate the feasibility of converting slash into wood products and energy.

Preprocessing--This permits optimum grading and distribution of all harvested material. Early conversion of low-grade slash material into uniformly sized chip material increases processing and transportation efficiency. The following processes may encourage maximum use of low-grade slash material.

> Merchandising centers--Such centers combine sorting and some processing to divert logs to specialized centers of use. Low-grade logs and slash materials are typically chipped for transport to nearby mills as pulp or hog fuel material.
>
> Chip and saw--Chip and saw mills utilize small log materials for stud material and maximum residue recovery. Material that has no lumber value is chipped and utilized as hogged fuel or transported to nearby pulp mills.
>
> Chipping plants--Chipping plants and mobile chippers provide early or on-site processing of slash material into chip form for transport to nearby mills. The economic feasibility of these processes are extremely dependent on fluctuating chip markets (Gram 1974).

Hammermill plants--Hammermill plants and portable machines are being developed to provide early or onsite production of uniformly sized and compressed wood pellets for efficient handling and transport (Currier 1971).[18]

Stockpiling of slash material or processed chips can be used for short-term storage when markets are not favorable for material utilization. Chemical control methods to reduce deterioration of stockpiled wood fiber are being developed by the USDA FS (Young 1972).

Transportation--The transportation of slash materials is presently limited to the capability of standard logging trucks. These trucks are designed to haul uniformly shaped material and cannot accommodate smaller, irregularly shaped slash material. New and modified hauling systems are available that may increase the efficiency of slash handling.

Short truck and trailer--These combinations have been developed for small log handling. These vehicles can accommodate log material that is too short for standard logging trucks.

Chip vans--Chip vans may be used in combination with onsite chipping or wood-pelletizing processes. Uniform material size allows efficient transportation to mills.

Sideboard modifications--Improvements to standard logging trucks may allow "whole-tree" transporting. This is a new concept being developed by Weyerheauser Company in the Southeast with potential, but as yet untested applications in the Pacific Northwest.[19]

Production processes--Many forest product industries can presently accommodate, or be modified to efficiently use, slash material. The basic properties of slash material are not significantly different from the fiber used in any wood product. Increasing use of mill residues demonstrates the existing potential for utilizing slash type materials. Sound fiber can be used as fuel for steam to generate electrical power. Slash materials can also be used to a much lesser extent for other miscellaneous products. Table 25 shows the types of wood products presently available or being developed that could utilize slash fiber material.

Pulp and paper--The pulp and paper industry and chip export market offer the most feasible immediate use for slash materials. Improved chemical pulp digestion processes can accommodate the unbarked rough wood of various hard- and soft-wood species. These processes produce diverse product lines with

---

[18] As cited in Van Vliet (1971).

[19] Personal communication, R. Cornelius, Wyerhaeuser Company, January 17, 1978.

TABLE 25. WOOD PRODUCTS FROM SLASH

Products	Process or Technique	Development or Research Group	Reference	Uses
Pulp	Sulfate, kraft	--	Grantham 1974	Paper products
Particle board	N/A	USDA-FS Forest Products Lab.	Dickerhoof 1977	Counter tops, underlayments, paneling, decking
Structural flakeboard	N/A	USDA-FS Forest Products Lab.	Adams 1976	Wall and roof sheathing, paneling
Charcoal	Herreshoff reduction furnace	Olsen Lawyer	Steffensen 1971 *	Recreation
Wood pellets	Pelletizing	Bio-Solar Research & Dev. Corp.	ITF-FSU 10/25/77	Electric generation, steam boilers
Fire wood	--	--	--	Home heat, hogged fuel
Methanol /Oil	Pyrolysis	N/A	Grantham 1978	Heat, steam boilers
Synthetic natural gas	Chemical catalyst	Battelle Memoiral Institute	Feldmann, H.F.†	Home heating, industrial applications
Densified fuel logs	Compression	USDA-FS Forest Products Lab.	Oregon State Univ., 1977	Presto-logs, home heating, stoker fuel
Resinous glues	Pyrolytic converter	Georgia Institute of Tech.	Howlett 1972	Bonding agent
Compost & soil conditioner	Pelletizing	University of Arizona	Fuller 1966	Landscaping, agricultural
Thermosetting plastics	N/A	Oregon State University	Currier 1971*	Molded products: cups, switch box, sofa leg
Glucose	Cellulose hydrolysis	N/A	Grantham 1978	Animal feed, carbohydrate supplement, sugar
Ethylene, butadiene	Ethanol extract	N/A	Grantham 1978	Alcohol
Absorbent floor covering	Hamermill sawdust	N/A	Harkin 1969	Animal bedding, packing plants, fish markets
Porous brick and tile	N/A	N/A	Harkin 1969	Reduced density and weight of clay products
Packing material	N/A	N/A	Harkin 1969	Shipping fragile items
Posts and stakes	--	Boise Cascade Corp.	Elmgren 1977	Grapestacks, fence posts
Cellulose derivatives	Dissolved pulp	N/A	Grantham 1978	Cellophane, rayon
Furan	Furfural extract	N/A	Grantham 1978	Nylon
Cork and wax	From Douglas-fir bark	N/A	Trocino 1974‡	Miscellaneous

* As cited in Van Vliet 1971 † USDOE study in progress ‡ As cited in Young 1975

satisfactory strength and bleach quality (Auston 1973). The bark content of processed material has been shown to increase total fiber yields by as much as 10 percent; nonfibrous bark material that is dissolved during the digestion process can be recovered and used by the mill as an energy source. The successful operation of a hardwood pulp mill by Weyerheauser Company in Aberdeen, WA suggests that concentrated red alder and other low-grade hardwood species in the coast range can support hardwood pulp mills.

The feasibility of utilizing slash material for pulp and paper is presently limited by market conditions and individual mill capabilities. As long as large amounts of cheaper, more desirable conifer mill residues are available, there appears to be little industrial incentive to use slash material.

Particle and flake board--Existing product lines of particle and flake boards are potential uses for slash materials. The particle board share of the Nation's wood-based panel industry has steadily increased from 5 percent in 1962 to 25 percent in 1972 (Buongiorno 1977). Structural flake board, a high strength wall and roof sheathing board, is still in the development stage (Heebink 1974). Construction applications are expected to be wide, especially in the housing market. Price and performance specifications are competitive with other product lines.

At this time, slash materials are not used for particle board manufacturing in the Pacific Northwest (Dickerhoff 1977). Cheaper mill residues constitute the entire raw material supply for these products. Research is ongoing to develop board products and material handling systems that might increase the use of slash materials (Zerbe 1972, Resch 1977).

Energy--Conversion of low grade slash material into energy products is technically feasible. Direct combustion of hogged slash fuels can be used to produce heat, process steam, and generate electricity for industrial and municipal use. A communal group in the Eugene-Springfield area is showing the cost effectiveness of harvesting slashed material for use as home fuel. The heat value of slash materials depends on the species and moisture content of the wood. Table 26 shows the heat value of various tree species' components on an ovendried basis. Increasing moisture content will significantly decrease the combustion efficiency of wood fuels.

Forest industries use large amounts of processed steam and heat. Pulp and paper production requires steam for pulp cooking and drying. Sawmills and plywood plants use direct heat for drykilns and veneer drying. Many of these facilities employ fuel systems that can accommodate hogged slash fuels. The use of slash material by forest industries for in-plant energy production is a function of the availability and cost of conventional energy sources.

---

[20] As cited in Grantham (1974).

At present, very little slash is being used. Processed mill residues, fossil fuels, and electricity provide most of the energy needs of industry. However, the scarcity of fossil fuels and potential price increases for industrial electricity users could result in the increased use of mill residue and slash material for energy in the near future.

TABLE 26. HEAT VALUES OF VARIOUS PNW TREE SPECIES

Species	Heating Value (Btu/lb, oven-dry*		
	Wood	Bark	Needles
Douglas-Fir	8,890	9,790	N/A
Western Hemlock	8,410	9,400	N/A
White Fir	8,210	N/A	N/A
Western Red Cedar	9,700	8,790	N/A
Ponderosa Pine	9,110	N/A	8,478
Western Larch	N/A	8,280	7,999
Lodge Pole Pine	N/A	10,260	9,050
Western White Pine	N/A	9,090	8,674
Red Adler	7,990	8,410	N/A

* These heat values are in contrast to 11,000 - 14,000 Btu/lb expected from coal.

Figure 23 shows the present sources of energy consumed by the pulp and paper industry. Mill residues provide 54 percent of all energy needs. The remaining 46 percent is supplied by fossil fuels and electricity. Efforts by forest industries to become more energy self-sufficient have been focused on the increased use of processed mill residue and are not expected to have an substantial impact on slash utilization.[21]

Slash material may be a potential energy source used to increase the electrical power generating capacity of Washington and Oregon. The U.S. Department of Energy is studying the feasibility of utilizing wood fiber to produce additional power for the regional power grid (Lindsey 1977).[22]

The forest industries are at present best suited to handle and process hogged slash fuel for electric power generation. Public utilities cannot compete with the forest industries for hogged mill residue and processed slash (Grant 1977).[23] Power is a logical secondary product of mills that now generate low pressure process steam. Conventional energy systems would require modifications to accommodate hogged slash material. The power generated by these small industrial units is expected to be more expensive than the public utility grid using conventional energy sources. These conversion and higher generating costs would necessarily be absorbed by the power grid in a "wheeling process" that would distribute power to all industrial and nonindustrial users at a cost reflecting the average operating cost of the total power grid.

---

[21] Personal communication, R. Cornelius, Wyerhaeuser Company, March 22, 1978.

[22] As cited in Adams (1977).

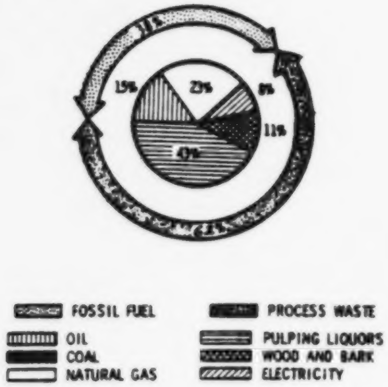


Figure 23. Energy consumption by the pulp and paper industry of the Pacific Northwest including California (Arola 1976)

The potential use of wood fiber for municipal steam and electric generation has been demonstrated by the Eugene Water and Electric Board (Lynch 1977).[24] The city of Eugene, OR employs hogged fuel fired boilers to produce steam heat. This system is also able to generate limited amounts of electricity, but at costs that are almost twice as high as power presently available from BPA.

The conversion of slash materials into other energy products is in the research and development stage. Potential conversion processes are described in Table 27. Although these processes may be technically feasible, they are not presently cost efficient alternatives for slash utilization.

---

[23] As cited in ITF-FSU Minutes, October 13, 1977.

[24] As cited in Adams (1977).

TABLE 27. CONVERSION OF SLASH INTO ENERGY PRODUCTS

Technique	Product	BTU/lb	Researcher	Reference
Pelletizing process (WOODEX)	Wood pellets	9,000	Bio-Solar Research & Development Corp.	ITF-FSU 1977
Pelletizing process	Pellets	7,960	Alsid, Snowden & Associates	Snowden 1977
Pelletizing process	Pulverized pellets	8,200	U and I, Inc.	Wilson 1977
Anaerobic digestion	Methane gas	N/A	N/A	Grantham 1974
Gasification reactor	Gas	150 (BTU/cu ft)	Council of Forest Industries of B. C.	Halak 1977
Pyrolysis by direct heating	Gas	N/A	USDA-PNW F&Res.	Grantham 1974
Pyrolysis by direct heating	Gas	8,200-9,600*	Forest Fuels, Inc.	Forest Fuels 1976
Pelletizing process (WOODEX)	Gas	8,700	Bio-Solar Research & Development Corp.	ITF-FSU 1977
Pyrolytic converter	Oil-soaked char	13,000	Georgia Institute of Technology	Howlett 1972
Pyrolytic converter	Wood oil	13,000	Georgia Institute of Technology	Howlett 1972
Catalytic procedure	Oil	17,000	USDI Bureau of Mines	Grantham 1974
N/A	Oil	N/A	Bechtel Corporation (USDOE)	Blackman 1978

* Depends on species

Pelletized material--Pelletized material uses a hammermilling process to reduce wood and bark residues to uniformly compacted and dried pellets. Pellets are an easily handled fuel with predictable burning characteristics. The fuel has been successfully used as a low emission substitute to coal and hogged fuels in the Pacific Northwest (Farnsworth 1977, Dell 1977).

Methane--Methane gas can be produced from wood residue using pyrolysis or anaerobic digestion. Small gasification units are capable of producing enough heat for veneer drying and other forest industry applications (Dell 1977).

Synthetic crude oil--The processing of synthetic crude oil using wood residues is being studied by the USDOE. A pilot plant at Albany, OR produces approximately three barrels of oil per day. However, costs are not competitive with presently available oil (Blackman 1978).

No Treatment

Desirable levels of slash abatement for sustained wood fiber production and wildfire hazard reduction cannot presently be accomplished by natural processes. Natural processes are slow. Slash degradation by wildlife, insects and microorganisms may take from 5 to 50 years depending on the slash component size, species, moisture content, temperature and inoculum present. Table 28 shows the natural decay process expected over a 15-year period in a western hemlock-type forest.

TABLE 28. NATURAL DECAY PROCESS OF WESTERN HEMLOCK (MacBean 1941)*

Years since logging	Stage of decay
1 - 3	Needles dry out and have mostly fallen. Fine twigs become brittle but still adhere to the branches.
4 - 6	Twigs flatten out.
7 - 9	Twigs less than 0.25 inch (0.64 cm) diameter have fallen. Small branches can be easily broken.
10 - 12	Slash well flattened, material less than 0.5 inch (1.3 cm) has fallen. Small logs become well rotted.
13 - 15	All small material decomposed. Small branches 2 to 3 inches (5-8 cm) in diameter still intact. Decay in logs well advanced.

* As cited in Ruth and Harris 1975.

The concept of introducing microorganisms into concentrated slash to hasten decomposition has been studied, but not applied. Lindermuth and Gill (1959)[25] found that slash decomposition can be accelerted by introducing specific wood-rotting fungus. The application of nitrogen fertilizers has also been found to stimulate wood decaying microbial activity.

Supplemental fire protection personnel may reduce wildfire damage in areas where no slash treatment is performed. Present applications by the USDA Forest Service are used in conjunction with fuel breaks or fire lines. Fire management personnel suggest that supplemental fire protection is not sufficient to reduce the wildfire hazard of heavy contiguous slash areas.

Untreated slash material may add to soil stability, provide shade for regeneration seedlings and maintain an organic nutrient source. However, these materials may also degrade adjacent surface water quality by clogging stream channels and increasing biochemical oxygen demand (Notzon 1977). There is indirect evidence that wood leachates may also be toxic to fish (Evans 1973).

THE ECONOMICS OF FORESTRY BURNING

An in-depth economic analysis of forest burning and of alternate methods of slash disposal requires detailed cost data for the following reasons:

1. The amount of variation in both the cost and the benefit data precludes the use of summary statistics, such as a mean value, as a meaningful representation of either costs or benefits.
2. The intangible burning and nonburning benefits are even more difficult to define in economic terms thus making it difficult to define the entire set of benefits without detailed data analysis.
3. Inadequate or contradictory summary data prevent the definition of burning and nonburning costs and benefits in the economic terms required for a reliable economic analysis.

Studies designed to evaluate the economics of slash disposal are, for the most part, localized and nonuniform. The detailed data may be available in the files of industrial firms utilizing various methods of burning or else making use of alternate methods of slash disposal. However, if these data exist, they were not made available for this study nor were they readily available in the open literature. The situation with the economic data was summarized by Adams (1976) when he stated "aggregate amounts (volumes) are misleading, and the potential value of logging residue, either positive or negative, can only be determined for specific situations with respect to the type of residue location, sale arrangements, and development of suitable processing facilities." Tables 29 and 30 represent examples of costs associated with burning and with nonburning methods of slash disposal. The range in values can be the result of either the limited, nonuniform cost data or the result of variability in the volume of residue per acre. Data are not reported for other potential alternatives because of their unavailability at the time of this study.

---

[25] As cited in Dell and Green (1968).

The classic benefit/cost formula calculates a ratio which provides a measure of the desirability of an investment by discounting the revenues and costs at an appropriate interest rate which is presumably the highest rate in the next best alternative use of capital. The discounted revenue stream is then divided by the discounted cost stream. If the benefit/cost ratio is equal to or greater than 1, then the project under scrutiny is considered justified.

There are typically two types of benefits and two types of costs associated with the benefit/cost ratio approach. The benefits can be divided into "project benefits" or as they are sometimes called "direct benefits" and secondary benefits sometimes called "indirect benefits." Project benefits consist of all benefits that come directly from the project while the secondary benefits are those that accrue to society because of the project. As an example, if slash were harvested, chipped, and processed into particleboard, one direct project benefit would be the wholesale price received for the particleboard. A secondary benefit would be the societal benefit of not having to view or inhale slash smoke because the slash was removed instead of burned.

Costs are also divided into two parts. The first part is comprised of "project costs." Project costs consist of the value of all goods and services used for establishing, maintaining, and operating the project purchases of land, labor, equipment, etc. necessary to undertake the project. The second part is comprised of "associated costs." These costs are incurred over and above project costs to make the outputs of the project available.

The questionable portion of any benefit/cost ratios is the inclusion of secondary benefits and the associated costs. There is a tendency to disregard those benefits that cannot be measured in concrete terms. Those benefits that are intangible, difficult to assign marketplace dollar values to (view, air quality, etc.), often find no place in benefit/cost analysis. Secondary benefits should be isolated and priced. Even though a benefit/cost ratio for slash removal may be less than 1, addition of the secondary benefits could cause the benefit/cost ratio to rise above the value of 1.

TABLE 29. COST EXAMPLES OF PRESCRIBED BURNING IGNITION DEVICES AND BURNING TECHNIQUES IN THE PACIFIC NORTHWEST

Ignition Techniques

Type	Cost	Organization	Reference
Primacord	$20.25/A	Publishers' Paper	Feddern (1977)**
Primacord (Helicopter)	$20.25-23.25/A	Publishers' Paper	Feddern (1977)**
Helitorch	$20/A	Publishers' Paper	Feddern (1977)**
Helitorch	$8/A	Washington	Griggs (1978)**

Burning Techniques

Organization	Cost	Reference
BROADCAST		
Washington	$121/A	FY(1974)
Washington	$121/A	Dell (1975)
Oregon	$73/A	Dell (1975)
Washington	$121/A	Dell (1975)
Oregon	$73/A	Dell (1975)
USDA-FS	$122-184/A	USDA-FS (1975)
USDA-FS	$4.10/T	Richardson (1976)
USDA-FS	$125-225/A	ITF-FSU (1977)
Industry	$25-110/A	ITF-FSU (1977)
Operator	$25-200/A	ITF-FSU (1977)
USDA-FS	$150/A	ITF-FSU (1977)
USDA-FS	(F)$80-120/A	Tokarczyk (1977)
USDA-FS	(SP)$90-140/A	Tokarczyk (1977)
Operator	(F)$100/A	Tokarczyk (1977)
Operator	(SP)$115/A	Tokarczyk (1977)
Forest Service	$140/A	Tokarczyk (1977)
Forest Service	$125-225/A	Dell (1977)
Industry	$85/A	Claunch (1977) **
Pretreatment		
Slash and Burn -		
Industry	$40-100/A*	Feddern (1977)**
Industry	$131/A	Feddern (1977)**
Brown and Burn -		
Forest Service	$86.72/A	USDA-FS (1973)
Pile and Burn -		
Washington	$79/A	FY (1974)
Washington	$79/A	Dell (1975)
Oregon	$55/A	Dell (1975)

(continued)

* Only slashing

** Personal communication

TABLE 29. (continued)

Burning Techniques

Organization	Cost	Reference
BROADCAST		
Pretreatment		
Pile and Burn -		
Forest Service	$560/A†	Richardson et al. (1976)
Forest Service	$4/T	Richardson (1976)
Forest Service	$105-200/A	Dell (1977)
Forest Service	$160/A	Tokarczyk (1977)**
Forest Service	$140/A	Tokarczyk (1977)**
Operator	$115/A	Tokarczyk (1977)**
Forest Service	$50-300/A	USDA-FS (1977)
PILE		
PUM		
Hand -		
Forest Service	$153-310/A	USDA-FS (1975)
Forest Service	$500/A	ITF-FSU (1975)
Oregon	$450/A	ITF-FSU (1977)
Forest Service and Operator	$125-175/A	Tokarczyk (1977)
Operator	$175/A	USDA-FS (1977)
Forest Service	$100-150/A	Tokarczyk (1977)**
Forest Service	$150/A	Getz (1975)
Machine -		
Forest Service	$117-164/A	USDA-FS (1975)
Forest Service	$100-200/A	ITF-FSU (1977)
Industry	$150-200/A	ITF-FSU (1977)
Forest Service and Operator	$100-120/A	Tokarczyk (1977)
Forest Service	$50-75/A	Getz (1975)
YUM		
Forest Service	$10/A‡	USDA-FS (1975)
Industry	$300/-$1,000/A	ITF-FSU (1977)
Forest Service	$352/A	Tokarczyk (1977)
Operator	$224/A	Shenk (1977)
Forest Service	$150-300/A	USDA-FS (1977)
Forest Service	$450-950/A§	ITF-FSU (1977)
Forest Service	$300-800/A	Dell (1977)

(continued)

† At 40 tons/acre

‡ Only burning

§ YUM and burn

** Personal communication

TABLE 29. (continued)

Organization	Cost	Reference
AIR CURTAIN BURNER		
USDA-FS	$30/ton	Ward (1976)
USDA-FS	$16-30/ton	McLean & Ward (1976)
USDA-FS	$6-8/ton	Harrison (1975)
USDA-FS	$8/ton	Murphy & Fritschen (1970)
USDA-FS	$585/AC	Lambert (1972)*
Washington	$14/ton	Golson (1975)

* As cited in Fahnestock (1975).

TABLE 30. COST EXAMPLES OF NONBURNING TECHNIQUES IN THE PACIFIC NORTHWEST

Mechanical Techniques			
Organization	Type	Cost	Reference
Masticate			
USDA-FS	crush	$20/AC	Dell & Ward (1969)
Industry	slash	$40/AC	Feddern (1977)
USDA-FS	Tomahawk	$30/AC	Dell (1977)
USDA-FS	Hydro-Ax	$70-90/AC	Dell (1977)
USDA-FS	Trak-Mac	$70-90/AC	Dell (1977)
USDA-FS	crush	$18/AC	Wilson (1970)
USDA-FS	crush	$20/AC	Murphy & Fritschen (1970)
Washington	Hydro-Ax	$15-30/AC	Mohler & Golson (1975)
USDA-FS	Tomahawk	$20-35/AC	Shenk & Harlan (1972)
USDA-FS	Marden Brushcutter	$11-19/AC	Dell & Ward (1969)
USDA-FS	Tomahawk	$19-29/AC	Dell & Ward (1969)
Washington	Trak-Mac	$137-239/AC	Mohler & Golson (1976)
Chip			
USDA-FS	small portable	$3/ton	Schimke & Dougharty (1966)
N/A	N/A	$1, 600-2, 800/AC	Lambert *
USDA-FS	small portable	$150-200/AC	Dell (1977)
Pile			
USDA-FS	PUM	$66-110/AC	Baker (1977)
USDA-FS	YUM	$300-800/AC	Dell (1977)
USDA-FS	PUM	$75/AC	USDA-FS (1977)
USDA-FS	PUM (hand)	$120-500/AC	Dell (1977)
Scarify			
USDA-FS	tractor	$12-22/AC	Dell & Ward (1969)
USDA-FS	HLS	$244-264/AC	Ward & Russel (1975)
Bury			
USDA-FS		$74/AC **	Schimke & Dougherty (1966)
USDA-FS		$83/AC **	Ward (1976)
N/A		$1, 800/AC	Fahnestock (1974)

* As cited in Fahnestock (1974)

** At 50 tons/acre

Existing cost data are quite varied and, as a result, not useful for benefit/cost analysis. One important aspect that may be derived from the data is the variability itself. The estimates of the cost of prescribed burning vary greatly from source to source. This variance can be attributed to many factors. If one assumes that all costs collected have been collected uniformly, there is great variability in cost of slash burning from acre to acre. However, the variance may be attributed to nonuniformity of the data collected. Some sources report the cost of slash burning on a per-ton basis instead of a per-acre basis. Some sources present only the cost of materials involved in actually setting the fire, some give a collection of costs, and yet other sources present the costs in terms of pretreatment costs and then burning costs. In order to conduct a meaningful analysis of costs and benefits, a set of uniform detailed data is required.

Items that can be generally identified as lacking in the available cost data may be described as:

1. Uniform data not available.
2. Irregular grouping of costs.
3. Slash burning cost data are lacking.
4. Nonburning alternatives cost data are lacking.

Additional data lacking to complete a benefit/cost analysis are the benefits that accrue when slash burning is accomplished and the benefits that accrue when nonburning alternative methods are considered.

Scope of Phase II Economic Approach

Specific guidelines for a full benefit/cost approach to the alternative burning techniques and alternatives to forestry burning need to be identified. The guidelines must include specifications as to exactly what type of data needs to be collected and on what alternatives. After the Phase I portion of the study is completed, a study management group should identify specific burning and nonburning alternatives for slash disposal. Specific categories must be identified in each area and uniform cost data must be collected. As an example, the following methods of slash disposal may be defined:

Nonburning Alternatives	Burning Alternatives
Sell for Firewood	Pile and Burn
Haul for Energy Conversion	PUM Pretreatment
Haul for Paper Conversion	YUM Pretreatment
Bury	Broadcast Burn
No treatment	

Once the burning and nonburning alternatives for slash disposal have been identified, a uniform data collection approach may be adopted. Items for which data should be collected for each alternative are:

1. Labor

2. Materials

3. Equipment

4. Transportation

5. Associated Overheads.

The majority of the cost data may be present for the burning alternatives. The majority of the cost data may not be present for the nonburning alternatives. Benefits that accrue from the alternatives listed must be defined. Benefits must be viewed as either long- or short-term. A long-term benefit is the increased yields resulting on those acres that have been treated. A short-term benefit is the decrease in cost of planting as a result of slash treatment.

The proper approach to analyzing the economics of the burning and nonburning alternatives of slash disposal must be highly systematic. A study plan and simple study format for a Phase II economic approach are outlined in Appendix B.

As time proceeds, favorable tax legislation regarding the use of slash material may alter benefit/cost ratios. Future tax credits and tax exemptions may make previously undesirable alternatives more attractive. Consideration must also be given to the effect that slash disposal alternatives have on the yields of other multiple-use products of the forest (including range, water, wildlife and recreation).

The analysis would include secondary benefits and associated costs that accrue from items such as:

1. Fire hazard reductions

2. Seed bed preparations

3. Physical impediment reductions

4. Silvicultural considerations

5. Health cost reduction through air quality improvement

6. Esthetic values of visibility improvement.

These items are difficult to quantify. The benefits and costs should include all known values for those benefits and costs that currently have no value in dollar terms attributed to them. Additionally, benefit/cost ratios may vary with geographic location. The benefit/cost ratio for one alternative may be greater in one area and far less in another area. Differences in species, slope, elevation, underbrush, and previous logging activity may play a role in the benefit/cost determination.

SECTION 6

FUTURE IMPACT OF FORESTRY BURNING ON AIR QUALITY

The future impact of forestry burning on air quality in the Pacific Northwest is a function of the level of burning, Federal, state and local air quality regulations and the use of alternatives to burning. Historical trends may not be useful in a projection of future impacts because of significant changes in burning technology, regulations and alternatives within the past 5 to 7 years. This section characterizes some of these recent trends and their potential impact on air quality.

IMPACTS OF PROJECTED TRENDS IN BURNING

The future of slash burning can be categorized into short- and long-term trends. The need for prescribed burning may increase on a short-term basis.[1] More burning is expected due to favorable productivity and cost incentives and improved burning technology and methodology. By the year 2020, most old growth timber will have been harvested, leaving commercial stands in harvest cycles of 60 to 100 years.[2] Better utilization and management control of these second growth stands are expected to create less slash, therefore decreasing the need for slash disposal.

Between 1972-77, the number of acres of slash burned in the Pacific Northwest showed an increasing trend for both Washington and Oregon (Figure 24). However, the trend of total tons burned varied with Oregon increasing, Washington decreasing and the region as a whole remaining constant (Figure 25). The proportional amount of slash burned measured in tons/acre decreased for both Washington and Oregon (Figure 26). These trends are independent of two abnormal data sets. The 1974 data for Oregon used in these figures were incomplete due to a computer malfunction. The 1976 data for both states reflects an unusually high level of burning due to extremely favorable weather conditions.

Although there appears to be little change in the total tons of slash being burned in the region, the downward trend of the amount of slash burned per acre may reduce the impact of forestry burning on air quality in the area of the burn. This trend in the amount of slash burned per acre corresponds with a continuing trend towards more complete utilization of the wood harvested and with more precise techniques for estimating the amount of fuel burned, an estimate which historically has been on the high side. The use of broadcast burning appears to be in an upward trend in Oregon. The number of acres broadcast burned in Oregon increased 48 percent during the 3-year period from 1975-1977; concomitantly, pile burning decreased by 14 percent (Figure 27).

---

[1] ITF-FSU, Final Report, December 1977.

[2] Personal communication, J. Todd, USDA FS, October 1977.

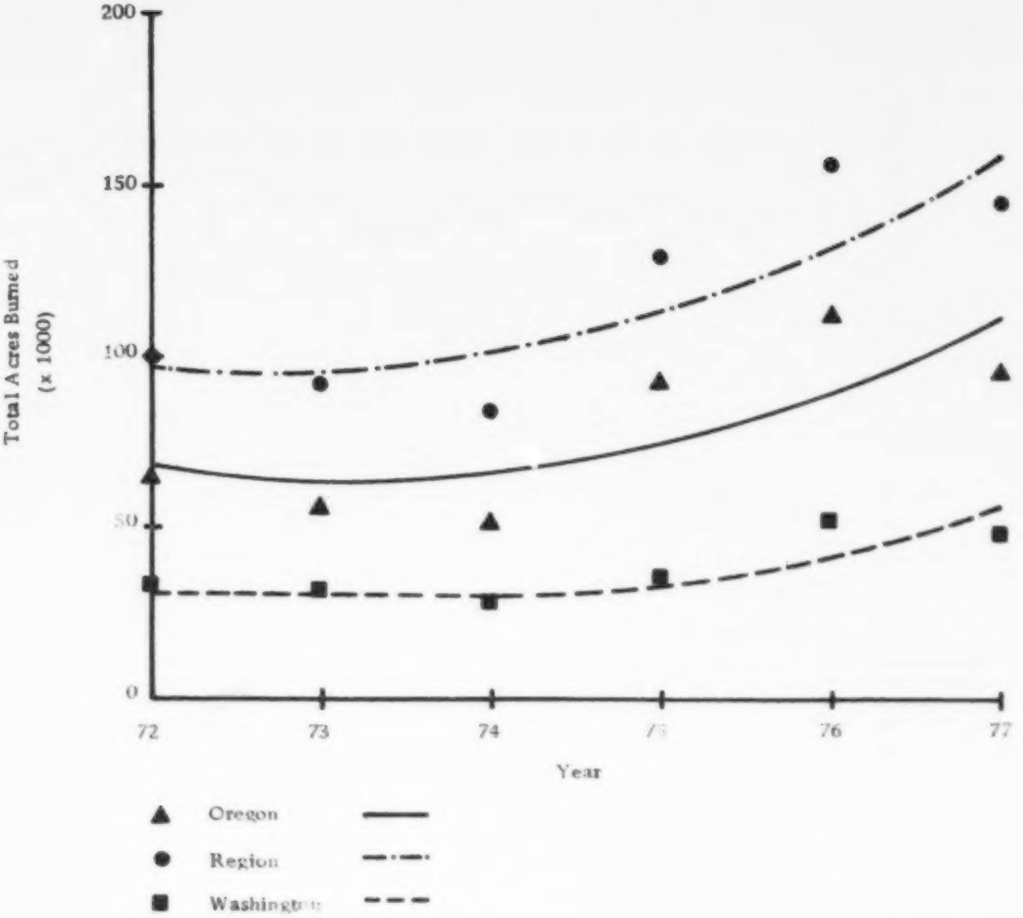
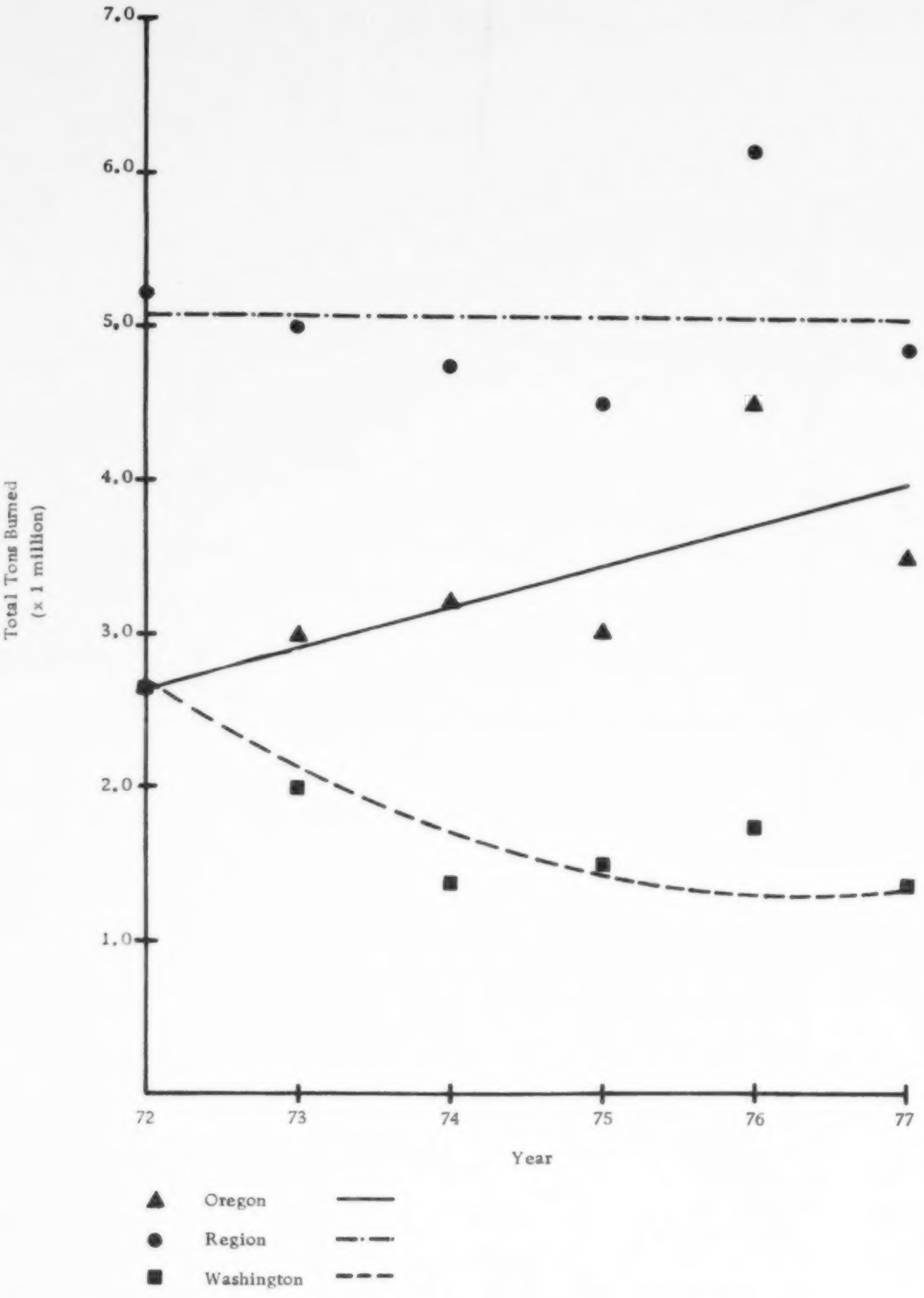
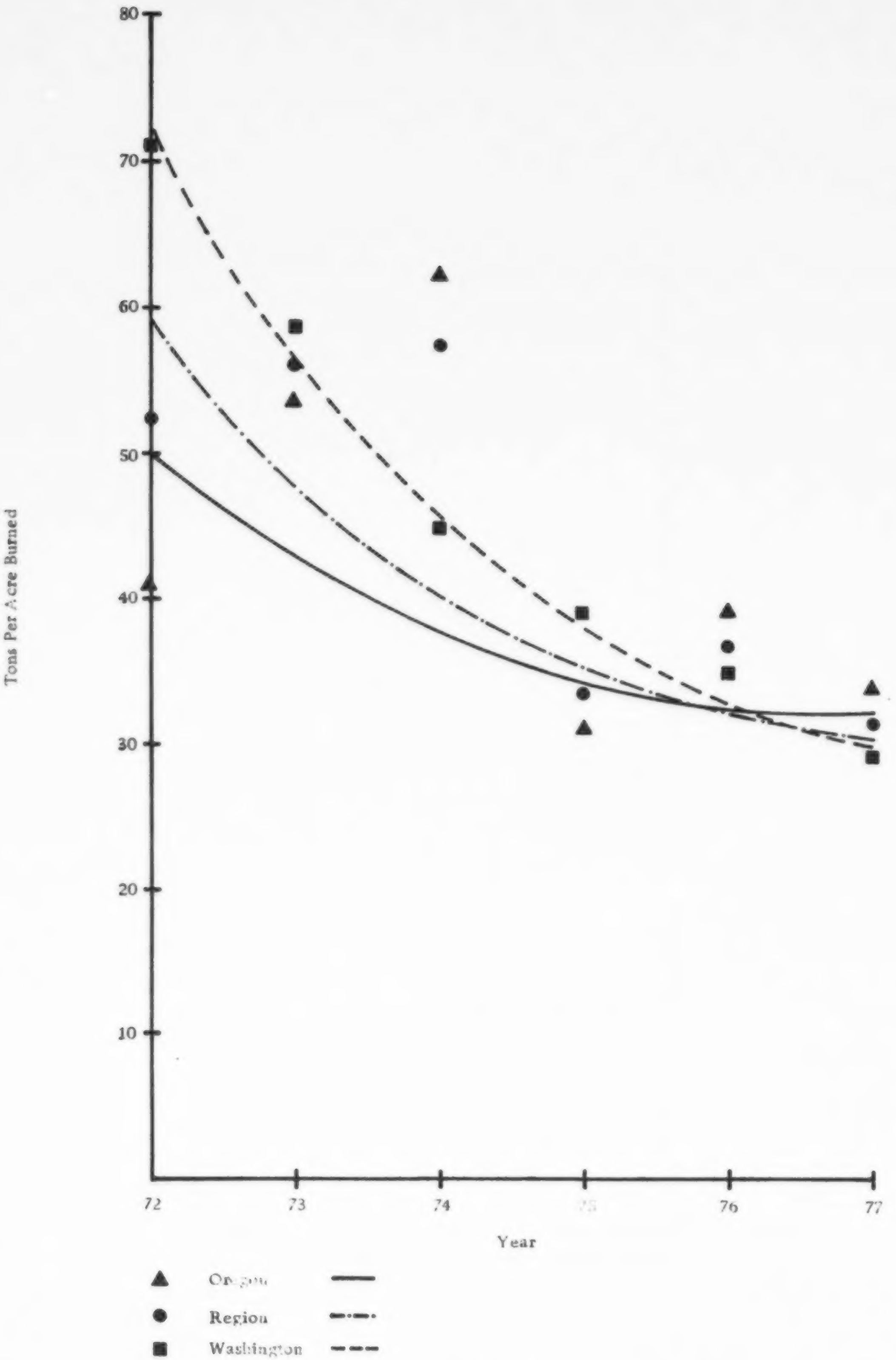


Figure 24. Trend of acres burned on the West Side from 1972-77.



NOTE: Tonnage figures are estimates and subject to possible error.
See page 43 for discussion of error.

Figure 25. Trend of tons burned on the West Side from 1972-77.



NOTE: Tonnage figures are estimates and subject to possible error.
See page 43 for discussion of error.

Figure 26. Trend of tons/acre burned on the West Side from 1972-77.

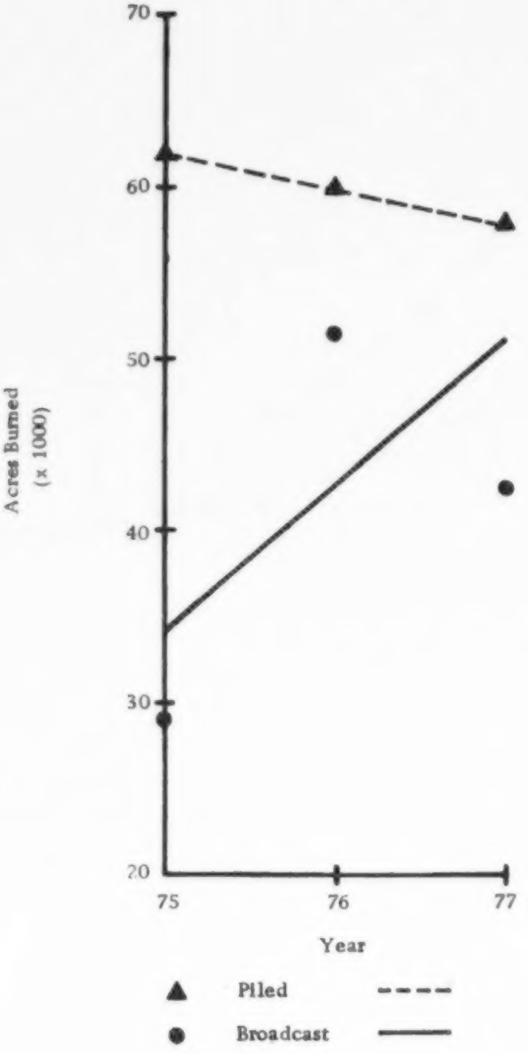


Figure 27. Three-year trend of broadcast and pile burning in Oregon. (Figures derived from Oregon SMP reports.)

Increased broadcast burning correlates with the recent increased use of fire for brushland conversion as reported by the Oregon Department of Forestry.[3] The downward trend in pile burning is contrary to the trend observed on National Forests from 1963 to 1972 (USDA FS 1973). Although no data are available after 1972, increasing use of partial cut timber harvesting methods on National Forests has led to the use of pile rather than broadcast burning.[4]

IMPACT OF AIR QUALITY REGULATIONS

There are two areas where pending or recently enacted air quality legislation is likely to have a significant impact on forestry burning as practiced in the Pacific Northwest. The first relates to a requirement by the Clean Air Act Amendments of 1977 that visibility impairment from man-made sources not be allowed in national pristine areas. The second relates to the possible development of National Ambient Air Quality Standards (NAAQS) specifically for fine particles.

The Clean Air Act classifies areas as either I, II or III. Class I areas are those in which almost any degradation of air quality would be considered a significant degradation. The Clean Air Act Amendments of 1977 declare as a national goal the prevention of visibility impairment from man--made air pollution and the restoration of natural visibility in mandatory Class I Federal areas. Twenty national parks and wildernesses of the Pacific Northwest have been declared as mandatory Class I areas. These are summarized in Table 31. The possible impact of this legislation on forestry burning as practiced in the Northwest is considerable. The Smoke Management Programs of both Oregon and Washington permit burning when the prevailing wind carries smoke away from populated areas. The operation of the program has been simplified by the fact that the populated areas of Washington and Oregon (at least west of the Cascades) generally coincide with the Puget Trough and the Willamette Valley. Hence, burning is generaly permitted in the Cascades when the prevailing wind is from the west and in the Coast Ranges when the prevailing wind is from the east. However, Class I areas are wilderness areas which frequently lie in the Coast or Cascade Ranges. If smoke is to be vented away from both populated areas and these Class I areas, the effect will be to make smoke management much more complicated operationally than it is currently or even impossible in certain commercial forest areas bordering these Class I areas. This is particularly true of burning in the Cascades, which contain 12 separate Class I areas.

Any visibility limitation would be particularly severe for broadcast burning. While pile burning could, in some areas, be carried out when visibility is naturally impaired during fog and/or rain, it is virtually impossible to carry out broadcast burning during these times. Hence, the visibility goals of the 1977 Amendments may be interpreted to restrict forestry burning more than current Smoke Management Program restrictions.

---

[3] ITF-FSU, Final Report, December 1977.

[4] Personal communication, J. Dell, USDA FS, March 27, 1978.

TABLE 31. CLASS I AREAS IN OREGON AND WASHINGTON*

Oregon	Washington
Crater Lake National Park	Alpine Lakes Wilderness
Diamond Peak Wilderness	Glacier Peak Wilderness
Eagle Cap Wilderness	Goat Rocks Wilderness
Gearhart Mountain Wilderness	Mount Adams Wilderness
Hell's Canyon Wilderness	Mount Rainier National Park
Kalmiopsis Wilderness	North Cascades National Park
Mountain Lakes Wilderness	Olympic National Park
Mount Hood Wilderness	Pasayton Wilderness
Mount Jefferson Wilderness	
Mount Washington Wilderness	
Strawberry Mountain Wilderness	
Three Sisters Wilderness	

* Federal Register, Vol. 43, No. 38. Friday, Feb. 24, 1978.

Reaction of forestry managers to the new visibility constraints could take one of two forms: first, a cutback in forestry burning as a management alternative in response to visibility restrictions (burning permitted only when smoke vented away from both populated areas and Class I areas); or, second, a lessening in the severity of population-oriented restrictions as currently detailed in the Smoke Management Programs of Washington and Oregon. In view of the potential impact that forestry burning may have on air quality in populated areas, this second alternative may not be desirable at this time. Furthermore, the first alternative may not be feasible in certain cases, if silvicultural and hazard reduction objectives of forestry practice are to be met. A careful analysis of the potential impact of the visibility requirement on air quality and forest management should be undertaken before visibility requirements are implemented. This analysis might start with an evaluation of commercial forest lands affected due to proximity to Class I areas and the degree of restriction on burning activity imposed by the visibility requirement, given prevailing meteorological conditions and proximity to populated areas. Without such an analysis it will be difficult to determine just how significant the impact of the new visibility requirement of the Clean Air Act will be on forestry practices.

The second area in which regulation could impact significantly on forestry burning is the potential for new fine particle air quality standards by the US EPA. Current air quality standards are based on 24-hour and annual geometric mean concentrations of particles less than 50 μm in diameter. However, it has been recognized for some time that fine particles less than 1 μm in diameter have a much more significant impact on the health than do larger particles. Furthermore, there is considerable evidence that much of the particulate emission from forestry burning is in the fine particle range (see Section 3). Hence, new standards for fine particles have the potential for significant impact on forestry burning activity. Dichotomous sampling, which records fine particle concentrations separately from large particles, and is part of the Oregon DEQ's new field monitoring program, will help to determine the contribution of forestry burning to fine particle concentrations. The knowledge gained from the field monitoring program will help air quality planners and forestry managers in planning corrective action if new fine particle legislation is passed.

IMPACT OF ALTERNATIVES TO BURNING

The future use of alternatives to forestry burning are limited by the development of efficient techniques that are technically feasible in the steeply sloped terrain of the Pacific Northwest. Alternative slash treatments may become more feasible as more low grade woodfiber is harvested for utilization. A trend towards greater utilization is apparent. The changing standard of the Simpson Lumber Company from an 11-inch minimum log diameter in 1967 to a 4-inch minimum log diameter in 1977[5] is characteristic of the changing utilization standards of the forest industries in the Pacific Northwest. Closer utilization standards are thought to be partly responsible for decreasing slash loads as shown previously in Figure 26.

The short- and long-term potential of harvesting slash for wood and energy products was not apparent in the literature reviewed or during the field interviews. However, this type of data may exist within the forest industries showing when mill residues will no longer be available and forest residues are likely to be increasingly utilized. Short-term demands for wood residue material are expected to be almost entirely supplied by mill residue as is presently the case (Table 32). The long-term demand for wood and energy products is expected to continue to increase. However, the economic desirability of harvesting slash materials may depend on the following factors:

- The availability of less expensive mill residues or other raw materials
- The increasing value of residue wood products

---

[5] Personal communication, M. Truax, Simpson Lumber Company, January 24, 1978.

- More efficient slash handling and transportation systems
- The increased demand for residue wood products.

TABLE 32. SOURCES OF WOOD RESIDUE MATERIALS USED FOR WOOD PRODUCTS IN THE PNW

Source	Particleboard* (%)	Pulp† (%)	Hog Fuel‡ (%)
Slash (Roundwood)	0	15 §	< 5
Veneer core	< 0.5	2	N/A
Planer shavings	74	8	N/A
Plywood mill waste	9	< 1	N/A
Slabs, edgings, and trimmings	4	< 1	N/A
Sawdust	10	7	N/A
Chips	2	61	N/A
Other	< 0.5	6	N/A
Total mill residue	100	85	> 95

* from Dickerhoof 1977

† from Austin 1973

‡ estimate based on personal communications with USDA FS and industry personnel

§ mostly utility grade logs

SECTION 7

REQUIREMENTS FOR IMPACT ASSESSMENT AND CONTROL

The major information gap encountered by GEOMET, Incorporated, in determining forestry burning impacts on air quality in Washington and Oregon, is the lack of definitive ambient air monitoring data, emission factors and dispersion studies. The lack of air monitoring data is obvious to all agencies and personnel concerned with either air quality or forestry burning in the Pacific Northwest. The major objective of the forestry smoke management plans is to restrict burning activity which may result in smoke intrusions into population centers. Smoke management is generally effective and intrusion of smoke into heavily populated areas is rare. Economic restrictions have limited state and local environmental agencies to deployment of air monitoring stations primarily in sensitive areas having the largest populations. Smoke management criteria for designation of "smoke-sensitive" areas are derived on a comparable population basis and have similar population limits. As a result, smoke management strives to avoid smoke intrusion into areas designated "smoke-sensitive," which are the only areas having active air monitoring installations. Smoke intrusions do occasionally occur, mainly due to unpredicted meteorological variations. Pollutant emissions from industrial point sources and transportation sources contribute to the monitored pollutant levels. All emissions are affected by the same meteorological variations, and smoke intrusions can not usually be unequivocally documented. The current situation in the Pacific Northwest thus precludes using air monitoring data for assessment of the impact of forestry burning on air quality.

The Oregon Department of Environmental Quality (DEQ) has made a number of attempts to monitor the impact of agricultural field burning in the Willamette Valley and has established an air monitoring network for this purpose. Normally, the periods of agricultural and forestry burning are coincident and separation of air quality impacts from the two is very difficult. However, in late 1977, forestry burning was carried out for several months after agricultural burning had ceased. The DEQ air monitoring network was kept operational during this period and the data collected support a correlation between forestry burning and degradation of air quality. A more sophisticated DEQ air monitoring network is scheduled for deployment in 1978. This network is designed so that air quality impacts of forestry and agricultural burning should be separable from each other, as well as from industrial emissions from resident point sources.

The Willamette Valley is only one of many areas in the Pacific Northwest whose air quality is potentially degraded by smoke from forestry burning. However, no comprehensive effort to selectively monitor forestry burning emissions has been made in any of the other areas and no data, beyond occasional qualitative citizen complaints, exist for correlation between forrestry burning and degradation of air quality.

In order to arrive at meaningful conclusions regarding the current impact of forestry burning on air quality in Washington and Oregon, it will be necessary to conduct a comprehensive air quality survey to collect data and provide a basis for definition of specific regions vulnerable to such impact. The survey will need to be interfaced with a sophisticated analytical data reduction system and structured in a manner to identify both distant and proximal impacts from forestry burning activity. For example, slash fires west of the Cascade range frequently emit smoke plumes which drift eastward and may impair the air quality in population centers east of the mountain range. The fires also emit significant quantitities of residual smoke, which drifts from the fire site at ground level and may impair the air quality in nearby population centers.

Air quality measurements should include more than high-volume samplers for measurement of total particulate matter. Particle size measurements and chemical analyses of collected particulate material should be carried out at selected sites. The gaseous emissions from forestry burning may also impact on air quality; therefore, some stations should include instrumentation for measurement of carbon monoxide, hydrocarbons and nitrogen oxides. In view of the probable photochemical reactivity of forest fire smoke, it would be desirable to measure ozone and oxidants as well.

A comprehensive air quality survey, carried out immediately before, during and after the forestry burning season, would provide the data base necessary to assess the impact of current forestry burning practices on air quality. However, such a survey would not contribute significantly toward resolution of any problems identified. It would be preferable to undertake a large-scale program, utilizing the combined resources of forestry and environmental interests, both to identify and minimize forestry burning impact on air quality.

ORGANIZATIONAL NEEDS

A highly organized, fully coordinated and comprehensive effort is required to evaluate the impact of forestry burning on air quality in Washington and Oregon. Individual agencies pursuing narrow and diverse objectives could eventually generate sufficient information for partial evaluation. Separate efforts by forest industries and the USDA FS to minimize emissions through improved burning practices could decrease impacts in some areas. However, separate approaches would be time-consuming and costly. A single broad-scope, fully coordinated program, designed specifically to evaluate emission, dispersion, impact and economic studies and minimize emissions impact would utilize time and resources more efficiently and be more effective than multiple uncoordinated efforts. A diagram of an organizational structure capable of carrying out a program of the necessary scope is shown in Figure 28.

The total effort would be supervised by a steering committee drawn from agencies contributing funds, manpower or equipment to the program.

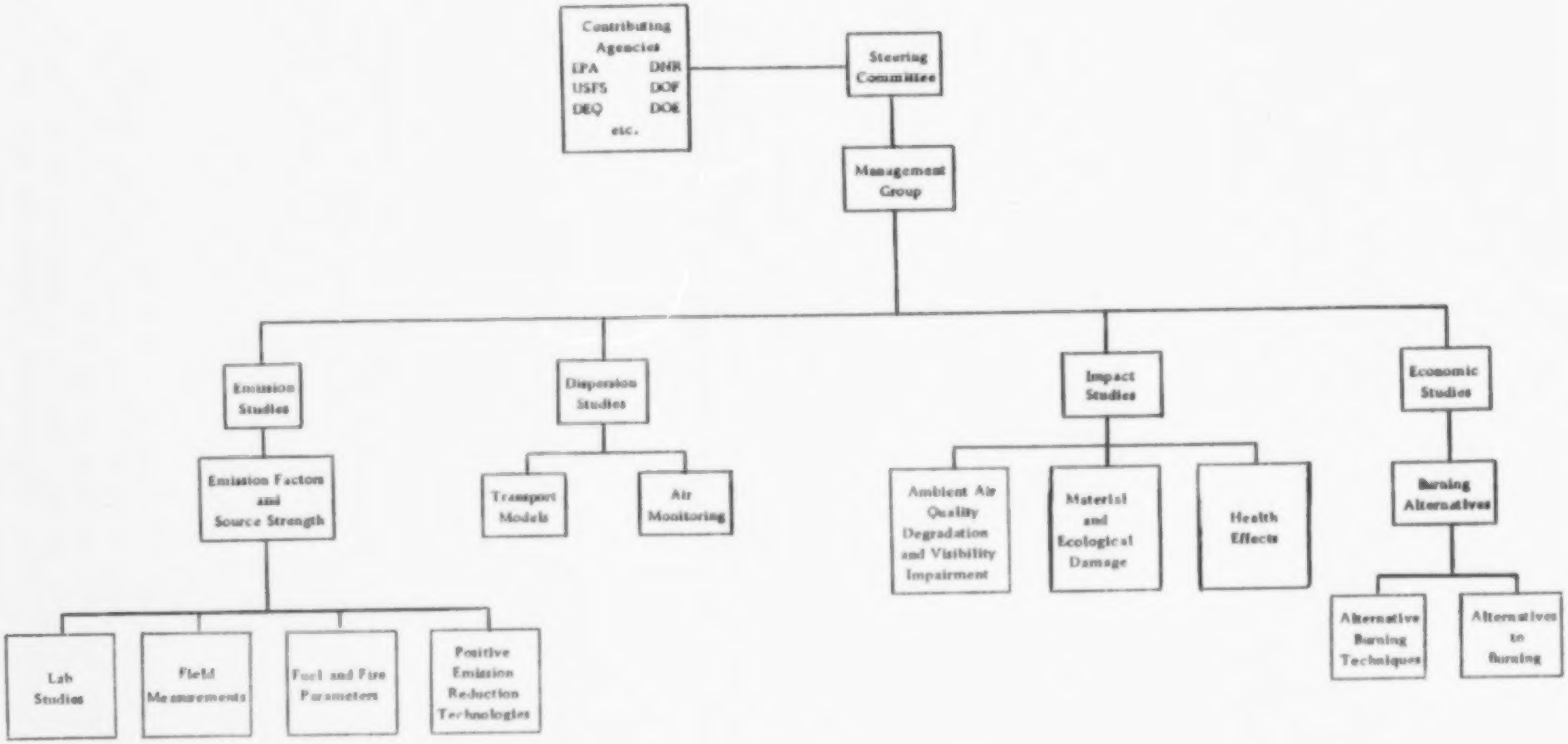

Contributing Agencies
EPA DNR
USFS DOF
DEQ DOE
etc.
Steering Committee
Management Group
Emission Studies
Emission Factors and Source Strength
Lab Studies
Field Measurements
Fuel and Fire Parameters
Positive Emission Reduction Technologies
Dispersion Studies
Transport Models
Air Monitoring
Impact Studies
Ambient Air Quality Degradation and Visibility Impairment
Material and Ecological Damage
Health Effects
Economic Studies
Burning Alternatives
Alternative Burning Techniques
Alternatives to Burning

Figure 28. Program structure.

Direct management of the project would be by a professional group responsible to the steering committee, preferably retained on a contract basis and not affiliated with any of the contributing agencies. The management group would create and be supported by a comprehensive data correlation and analysis system, which would continuously acquire data from individual projects and update the status of each to provide current information on individual and collective progress.

RESEARCH NEEDS

The end objective of a comprehensive research program would be capability for prediction of air quality impacts of fires through use of operation-oriented source strength and dispersion models. The functional inputs and interrelation of the two models are indicated in Figure 29. Detailed knowledge of fire behavior, for a burning technique suitable for the fuel type, condition and loading in a given situation, allows accurate prediction of source emission characteristics in terms of heat release rate, total emissions and emission rate as a function of time. These three predictions are the primary outputs of the source strength model. An important detail of the emission rate is the ratio of convective column to residual emissions. Transport and dispersion of the emissions are predicted by the dispersion model, which interfaces input from the source strength model with meteorological parameters to ultimately predict air quality impacts. Strategically deployed air monitoring networks are required to develop parameter values for the models and to evaluate their effectiveness in predicting air quality impacts.

Source Strength Models

Development of reliable source strength models requires detailed knowledge of fire behavior as a function of fuel and burning conditions. Fuel types, loading, arrangement and burning conditions in Washington and Oregon are diverse, and development of models to include most prevalent situations is a major effort. The primary factors forming the basis for such models involve fuel in a forest setting; forestry agencies must be heavily involved in any efforts undertaken in the area of source strength model development. Forestry agencies, notably the Southern Forest Fire Laboratory of the U.S. Forest Service, are actively engaged in research oriented toward development of source strength models. The accumulated experience and technology can be applied to model development for the Pacific Northwest. Studies in the areas of (1) emission factors and (2) fuel and fire parameters are required to provide the data base necessry for model development.

Emission Factors--

Emission factors are major determinants of source strength. Since they are highly fire- and fuel-dependent, they must be separately derived for the various fuel conditions and burning techniques of the Pacific Northwest. Derivation of emission factors requires a combination of laboratory studies and field measurements. Laboratory studies are carried

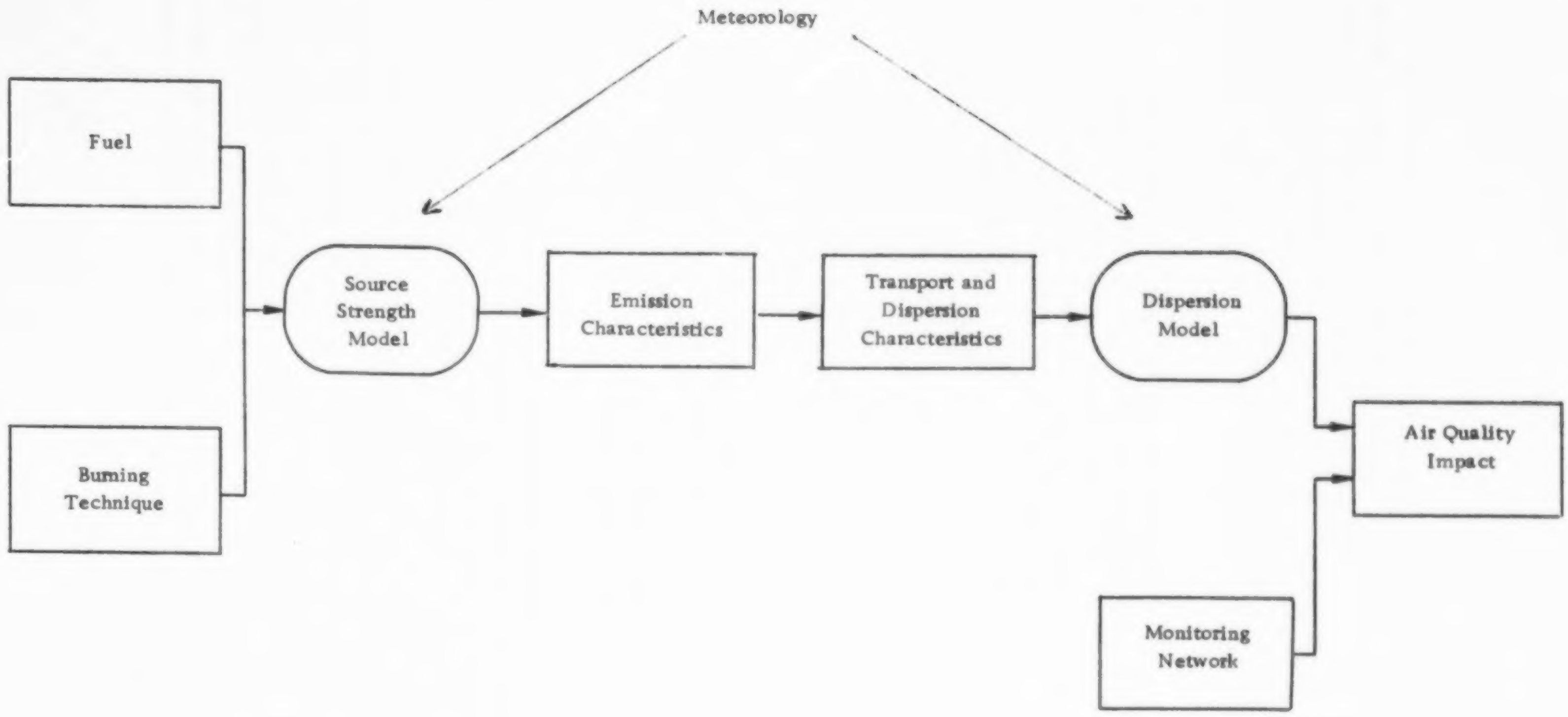

Meteorology
Fuel
Burning Technique
Source Strength Model
Emission Characteristics
Transport and Dispersion Characteristics
Dispersion Model
Air Quality Impact
Monitoring Network

Figure 29. Impact assessment.

out relatively easily and provide information useful in identification of fuel and fire variables that govern emission production. However, measurements of emissions from selected field fires must also be made to derive scaling factors for extrapolation of laboratory observations to field situations. A communication from John M. Pierovich, manager of the emissions research program at the Southern Forest Fire Laboratory, U.S. Forest Service, outlines the type of program and level of effort necessary for derivation of field emission factors:

> "Work in field sampling methods at the Southern Forest Fire Laboratory is currently focused on two key procedures. One procedural investigation is in the use of an array of instruments suspended by a tethered balloon in order to better profile smoke plume emissions concentrations near the fire. In this procedure, data from particulate matter and gas samples collected at different heights are related to coincident profiled air flow and temperature data, as well as to the amount of fuel consumed and fire behavior during the sampling period. The other procedure being studied will utilize laboratory and field-derived combustion/emissions relationships for simplified emission rate determinations using aircraft sampling. These rate relationships are to be used in a specified sampling protocol."

It is evident from the communication that derivation of field emission factors for forest fires is not an easy task. The high-intensity slash fires in complex terrain, typical of much of the burning in the Pacific Northwest, complicate the scaling of laboratory factors to field situations and increase the difficulty of making field measurements.

Fuel and Fire Parameters--

Fire behavior has a pronounced effect on emission factors, heat release rate and emission rate and is primarily determined by fuel type, loading, condition and arrangement. The reliability and predictive value of a source strength model are ultimately determined by the accuracy of the available fuel estimate and the reliability of the fire behavior prediction. The fuel and fire inputs to a source strength model largely determine the output. However, available fuel estimates and fire behavior predictions are operator-dependent, relying heavily on the training and skill of field personnel. The human judgment required cannot possibly be standardized, and significant variations between individuals and between judgments made at different times can be expected. A major focal point of the source strength study effort must be the development of standardized procedures and guidelines for estimating available fuel and predicting fire behavior. Improvements in the reliability and consistency of the estimates and predictions are directly reflected in the output of the model.

Dispersion Modeling

One of the most promising avenues for future studies of smoke impact is the use of regional-scale transport and dispersion models. Pollutant concentrations can be estimated for many locations by the use of such a model, provided detailed emission estimates are available. Some models are capable of yielding the contribution of each source to the total pollutant concentration computed for a particular location. In this manner the relative importance of slash burning in contributing to pollution problems can be assessed. Two such models are presently being validated against measured pollution concentrations in the Willamette Valley. However, improvements may have to be made to existing models as more knowledge is gained concerning air flow in complex terrain, the variations of mixing heights over mountainous terrain, and plume rise characteristics.

Additional monitoring and smoke plume studies need to be conducted before photochemical models are applied to regions surrounding forest burning activity. To date there is still too much uncertainty, concerning the hydrocarbon composition in smoke plumes and the chemical reactions by which photochemical oxidants form downwind of forest fires, to adequately model these effects.

An additional area for future research is the impact of longer-range transport of pollutants from slash fires. Air pollution control officials from eastern Washington (Jenne 1975) have attributed high TSP concentrations in the Pasco, Richland and Walla Walla areas in September and October, 1974, to slash burning in western Washington. Air trajectory models are necessary for tracing the long-range travel of smoke plumes. Trajectories are usually determined from wind observations at a number of locations throughout the area of interest. Although several regional scale, trajectory-directed dispersion models exist (e.g., Draxler 1977, Fabrick et al. 1977, Fosberg 1976, Liu 1974, Pandolfo et al. 1976), these need to be engineered and tested with regional data for practical application to evaluating the dispersion of forest burning emissions in the Pacific Northwest. An important process affecting the range dispersion of TSP is the removal of smoke particles from the atmosphere by precipitation processes. The important west-to-east differences in the precipitation process across the states of Washington and Oregon need to be taken into account. Although some models are available to treat the precipitation process and dry deposition (e.g., Dana et al. 1976), these need to be refined for application to this region.

Air Quality Monitoring

Little work has been done to directly assess the impact of slash burning on smoke-sensitive areas in the Pacific Northwest with the exception of the statistical and filter studies in the Eugene-Springfield area sponsored by EPA Region X and a recent monitoring study by the Oregon Department of Environmental Quality in the Willamette Valley. The use of hi-vol filters to determine the air quality impact of slash burning can be made more conclusive if a unique tracer element or compound for slash burning can be found. In the meantime, filters can be microscopically analyzed to determine the fraction of total particulate attributable to slash burning based on physical characteristics of the particles. If filter analyses are performed, both optical microscopy and scanning electron microscopy should be used to assure that the contribution of small particles to TSP mass is considered.

The methodology of assessing impacts on smoke-sensitive areas must be upgraded as evidenced by the discrepancies between the Oregon Department of Forestry and Department of Environmental Quality estimates of smoke intrusions into the Eugene-Springfield area. During the period from June 1975 through September 1977, the Department of Environmental Quality reported 92 days of smoke intrusions using only ambient TSP monitoring data. For the same period, the Department of Forestry reported only 21 days of smoke intrusions based on daytime visual observations. The attribution of these smoke intrusions should be related to burning data on a statistical basis.

Airborne monitoring instruments should be used to further investigate smoke plume structure and composition. Measurements of ozone and the precursors to photochemical oxidant formation (NO, NO_2, and hydrocarbons) are necessary in determining the nature of the chemical reactions and the extent of the ground-level impact of the oxidants downwind.

HEALTH EFFECTS STUDIES

Forest burning emissions of most interest in terms of potential health impact are CO, NO_2, respirable particulate matter, and halogenated vaporous compounds. Under the appropriate conditions, there appears to be the potential for oxidant formation distant from the burning site. Of these pollutants, particulate matter may be the most prominent consideration since some 80 percent of the forest burning particulate emissions are in the range of 0.1 to 1.0 μm in diameter. Particulate matter of this size could remain suspended for long periods of time and be carried considerable distance from the site of origin. These particles tend to be retained deeply in pulmonary passages with the potential of adversely affecting tissue due to particle composition and compounds adsorbed on their surface.

Particulate matter from combustion of carbonaceous material has long been considered a factor in the etiology of respiratory tract neoplasms and in chronic obstructive lung disease (COLD), although exposure-response relationships are not well documented. The major difficulty at this time in assessing the extent to which forest burning may impact health is the paucity of information on population exposure.

A carefully planned epidemiological study will be needed if the impact of forestry burning on health is to be fully assessed. Epidemiological studies are normally undertaken to identify causal factors in populations which experience abnormally high rates of diseases or combinations of diseases. A good example of such a study is the Montana Air Pollution Study (MAPS). MAPS has undertaken to determine contributions of air pollution sources to high rates of Chronic Obstructive Lung Disease in Montana. State officials observed that Montana had a considerably higher rate (22.4 deaths per hundred thousand) of deaths[1] due to asthma, emphysema and bronchitis than did the Nation as a whole (16.6 deaths per hundred thousand). Furthermore, the western, mountainous portion of the state experienced much higher mortality rates due to these diseases (27.1 deaths per hundred thousand) than did the remainder of the state (17.8 deaths per hundred thousand). MAPS is assessing the impact of forestry burning[2] on observed disease and mortality rates within Montana. The study will also evaluate the role of other factors such as elevation and socioeconomic variables on disease rates.

Mortality rates[3] for asthma, emphysema, and bronchitis are also high in several other northwestern states including Oregon (18.5 deaths per hundred thousand) and Washington (17.2 deaths per hundred thousand). A well-designed epidemiological study would help to determine the contribution of forestry burning, if any, to observed disease rates. The results of the Montana study, now in its early stages, should be weighed before undertaking a comparable study in Washington and Oregon.

RESEARCH IN PROGRESS

Numerous research studies pertaining to forestry burning techniques, alternatives, emissions and impacts on air quality are presently in progress. The following descriptors identify the organizations involved and briefly summarize ongoing research projects:

Southern Forest Fire Laboratory, U.S. Forest Service, Macon, Georgia.

> Comprehensive program including: Field sampling methods; Combustion/emissions relationships; Emission rate determinations; Emisions characterization; Smoke transport and dispersion; Smoke management.
>
> J.M. Pierovich, Program Manager, (912) 746-1477.

---

[1] All ages, deaths occurring from 1969 through 1973. Data supplied by Dennis Haddow, Department of Health and Environmental Sciences, State of Montana, July 31, 1978.

[2] The major source of particulate emissions in western Montana is forestry burning.

[3] Deaths for all ages during 1973. Comparable national figure is 14.2. Data supplied by Dennis Haddow, Montana Department of Health and Environmental Sciences, July 31, 1978.

University of Washington, School of Forestry, Seattle, Washington.

Nutrient volatilization on burning forest floor materials; Statistical properties of the line intersect fuel estimation method; Duration of flaming phase for large forest fuels.

S.G. Pickford, Senior Investigator, (206) 543-6210.

University of Washington, Department of Environmental Health; Seattle, Washington.

In vivo studies of toxic products from burning wood.

R. Schumacher, Coordinator.

Analytical techniques for measurement of combustion emissions.

L.E. Monteith, Principal Investigator, (206) 543-4252.

Department of Environmental Quality, Air Quality Control Division; Portland, Oregon.

Field and slash burning particulate characterization.

J.E. Core, Project Manager, (503) 229-6458.

Willamette Valley field and slash burning impact, air quality surveillance program.

F. Terraglio, Program Manager.

Oregon State University, Air Resources Center; Corvallis, Oregon.

Air quality model applied to field and slash burning in Oregon's Willamette Valley.

C.D. Craig, Principal Investigator, (503) 425-4955.

Washington State University, Air Pollution Research Station; Pullman, Washington.

Photochemical oxidant production and transport in forest fire smoke plumes over the Washington Cascades; Laboratory studies of hydrocarbon emissions from burning forest fuels.

H.H. Westberg, Principal Investigator (509) 335-1526.

Oregon State University, Department of Mechanical Engineering; Corvallis, Oregon.

Energy production from renewable resources.

R.W. Baubel, Principal Investigator, (503) 754-4902.

U.S. Environmental Protection Agency, Corvallis, Oregon.

Economic impact of air pollution on cost of timber production, crop production and household cleaning.

J. Jaksch, Program Manager, (503) 757-4714.

P.T. Tingey, Principal Investigator, (503) 757-4621.ission from plants.

University of Florida, Environmental Engineering, College of Engineering; Gainsville, Florida.

Photochemical reactions of smoke from burning pine needles and organic soil.

W.H. Benner, Principal Investigator.

Rocky Mountain Forest and Range Experiment Station, U.S. Forest Service; Fort Collins, Colorado.

Smoke dispersion studies applicable to complex terrain; Smoke management research.

M.S. Fosberg, Program Manager, (303) 221-4390.

Fuels management research.

S. Hirsch, Program Manager, (303) 221-4390.

Ministry of the Environment and Ministry of Forestry, Province of British Columbia, Victoria, British Columbia, Canada.

Air quality impact of slash burning.

K.A. Keshvani and P.A. Bell, Principal Investigators, (604) 387-5321.

Ministry of Forestry, Province of British Columbia, Victoria, British Columbia, Canada.

Smoke management research; Methods for estimating fuel loading.

D.E. Gilbert, Principal Investigator (604) 387-5965.

Pacific Northwest Forest and Range Experiment Station, U.S. Forest Service; Portland, Oregon.

Environmental effects of prescribed understoryburnings.

E.H. Clarke, Program Manager, (503) 234-3361, Ext. 4811.

Planning for prescribed burning in the Inland Northwest.

R.E. Martin and J.D. Dell, Principal Investigators (503) 221-2931.

Statewide Air Pollution Research Center, University of California; Riverside, California.

Impact of burning agricultural and forestry residues on air quality.

E.F. Darley, Principal Investigator.

Forest Products Laboratory, U.S. Forest Service, Madison, Wisconsin.

Research on saccharification of wood and conversion to energy chemicals and petrochemical substitutes; Improving combustion of wood, including processing methods such as charcoal manufacture, pyrolysis and briquetting.

J.I. Zerbe, Program Manager, (608) 257-2211.

United States Department of Energy, Richland, Washington.

Coordination of regional and national energy research. Studies include wood residue conversion to petrolium and gas products.

R.J. Durham, Special Projects Officer, (509) 942-6553.

United States Congress, Washington, D.C.

House of Representatives Bill 13324 introduced June 28, 1978 to establish pilot projects for testing and demonstrating practical application of existing technology for the utilization of wood residues from timber harvesting, forest protection and management, and the manufacture of wood products. (In committee.) Congressman James Weaver of Oregon, sponsor.

Appendix A

TREE SPECIES

Balsam poplar (Populus balsamifera)
Bigleaf maple (Acer macrophyllum)
Black cottonwood (Populus trichocarpa)
Boxelder (Acer negundo)
Douglas-fir (Pseudotsuga menziesii)
Engelmann spruce (Picea engelmannii)
Goldern chinkapin (Castonopsis chrysophylla)
Grand fir (Abies grandis)
Incense-cedar (Libocedrus decurrens)
Jeffery pine (Pinus jeffreyi)
Knobcone pine (Pinus attenuata)
Lodgepole pine (Pinus contorta)
Mountain hemlock (Tsuga mertensiana)
Noble fir (Abies procera)
Oregon ash (Fraxinus latifolia)
Oregon white oak (Quercus garryana)
Pacific dogwood (Cornus nuttallii)
Pacific madrone (Arbutus menziesii)
Pacific silver fir (Abies amabilis)
Paper birch (Betula papyrifera)
Quaking aspen (Populus tremuloides)
Red alder (Alnus rubra)
Red fir (Abies magnifica)
Redwood (Sequoia semperivirens)
Shasta red fir (Abies magnifica var. shastensis)
Sitka spruce (Picea sitchensis)
Sugar pine (Pinus lambertiana)
Subalpine fir (Abies lasiocarpa)
Subalpine larch (Larix lyallii)
Tanoak (Lithocarpus densiflorus)
Western hemlock (Tsuga heterophylla)
Western larch (Larix occidentalis)
Western red cedar (Thuja plicata)
Western white pine (Pinus monticola)
White alder (Alnus rhombifolia)
White fir (Abies concolor)
Whitebark pine (Pinus albicaulis)

APPENDIX B

Phase II - Economic Approach

Study Plan

Step 1. Organize a committee after the completion of Phase I.
2. Identify specific alternatives to slash burning.
3. Identify specific alternatives of slash burning.
4. Identify needed data concerning costs of 2 and 3 above.
5. Identify needed data concerning short-run and long-run benefits.
6. Make decisions on what non-valued benefits and costs that are present.
7. Identify sources of secondary data and investigate whether or not the specific data needed is present.
8. If data is not available, begin collection of primary data.
9. After all data has been collected, perform analysis and present rankings of alternatives.

Sample Study

Slash Burning Alternatives
- Broadcast Burn
  - a. head-fire
  - b. backing-fire
- Pile and Burn
  - a. Pum
  - b. Yum

Costs needed for each method:
- Materials
  - a. Ignition materials
  - b. Labor costs
  - c. Equipment costs
  - d. Transportation into and out of the area
- Non-valued Costs
  - a. Air quality premium
  - b. Visual premium

    (Note: if these premiums are set to remain constant over all the methods then no problem will exist. The problem that arises be in determining the difference in premiums as you proceed from broadcast burning to pile-burning. I would suggest that factors be used as multipliers to either increase or decrease the premium among methods.

Benefits needed for each method: (Project Benefits)

- Short run:
  - a. Amount of decrease in planting costs.
- Long run:
  - a. Increase or decrease in available volumes in the future as a result of burning.

Indirect benefits

- a. Improved site quality
- b. Reduction of fire hazard

Alternatives to Slash Burning

- No treatment
- Bury
- Haul Away (manufacturing or energy)
- Pile (PUM or YUM)

Costs needed for each method:

- Materials:
  - a. Equipment costs
  - b. Labor
  - c. Transportation
  - d. Increase in planting costs
  - e. Possible loss of long-term yield

Project Benefits:

- a. Return per unit if manufactured or used to create energy.

Indirect Benefits:

- a. Air quality premium
- b. Visual quality premium

When all the data for each specific alternative has been assembled, a formula to obtain a benefit cost/ratio may be employed. Possible rankings may be:

No treatment	1.05
Headfire	1.04
Backing fire	1.03
Pile and burn	1.02
Utilize for energy	0.75
Utilize for wood products	0.60
Bury	0.50

APPENDIX C

BIBLIOGRAPHY

INFORMATION SEARCH

The citations contained in this bibliography were identified by field experts and from the data bases shown below.

Computer Information Systems

PACFORNET
AGRICOLA
APTIC
NTIS
ENVIROLINE
COMPENDEX
CHEMLON
FIRE BASE
TOXLINE
ORBIT

Abstract Indexes

Forestry Abstracts 1971-1977

Hard copies were obtained from field experts or through the facilities shown below.

Publication Services

PACFORNET	Seattle, WA
NTIS	Springfield, VA
USDA-FS	Forest and Range Experiment Stations Pacific Northwest, Portland, OR Pacific Southwest, Berkeley, CA Southeast, Asheville, NC Intermountain, Ogden, UT Rocky Mountain, Ft. Collins, CO

Libraries

Library of Congress, Washington, D.C.
McKeldin Library, University of Maryland, College Park, Maryland
National Agricultural Library, Beltsville, Maryland
National Bureau of Standards Library, Gaithersburg, Maryland
National Oceanic and Atmospheric Administration Library, Washington, D.C.
U.S. Department of Agriculture Library, Washington, D.C.
U.S. Department of Interior Library, Washington, D.C.

Adams, Donald F., Robert K. Koppe and Elmer Robinson. 1976. "Air and Surface Measurements of Constituents of Prescribed Forest Slash Smoke." In *Air Quality and Smoke from Urban and Forest Fires Inter. Symp.* National Academy of Sciences. p. 105.

Adams, D.L. 1972. *Natural Regeneration Following Four Treatments of Slash on Clearcut Areas of Lodgepole Pine, A Case History.* Station Note 19. Moscow, Idaho Forestry, Wildlife, and Range Experiment Station. 2 pp.

Adams, T.C. 1976. *Economic Availability of Logging Residue in the Douglas Fir Region.* USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Resource Bulletin PNW-64. Portland, Oregon. 9 pp.

__________. 1977. *Energy from Dead Lodgepole Pine in Eastern Oregon.* USDA Forest Service PNW.

Adams, T.C. and R.C. Smith. 1976. *Review of the Logging Residue and Its Reduction Through Marketing Practices.* USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-48. Portland, Oregon. 22 pp.

Agee, James R. 1974. "Fire Management in the National Parks." *Western Wildlands* 1(3):27-33.

Agee, J.K. and H.H. Biswell. 1970. "Debris Accumulated in a Ponderosa Pine Forest." *California Agriculture* 24(6):6-7.

Albini, F.A. 1975. *An Attempt (and Failure) to Correlate Duff Removal and Slash Fire Heat.* USDA Forest Service General Technical Report INT-24. 16 pp.

__________. 1976. *Estimating Wildfire Behavior and Effects.* USDA Forest Service General Technical Report INT-30.

Alcock, J. 1977. *Forest Slash Utilization.* Smoke Management Subcommittee. October 6, Exhibit B. 10 pp.

Allan, G.G., C.S. Chopra, R.I. Gara, A.N. Neogi, and R.M. Wilkins. 1973. *Wood Waste Reuse in Controlled Release Pesticides.* Washington University, Seattle Institute of Forest Products Final Report. 96 pp.

Alsid, H.F. 1976. *Atmospheric Emission Evaluation - Western State Hospital Boiler #3.* Alsid, Snowden & Associates.

Anderson, Arthur B., King-Tsuen Wu and Addie Wong. 1974a. "Utilization of Ponderosa Pine Bark and Its Extract in Particleboard." *For. Prod. J.* 24(8):48-53.

Anderson, Arthur B., King-Tsuen Wu and Addie Wong. 1974b. "Utilization of White Fir Bark and Its Extract in Particleboard." For. Prod. J. 24(7):40-45.

__________. 1974c. "Utilization of White Fir Bark in Particleboard." For. Prod. J. 24(1):51-54.

Anderson, H.E. 1968. Sundance Fire: An Analysis of Fire Phenomena. USDA Forest Service Research Paper INT-56.

__________. 1969. Heat Transfer and Fire Spread. USDA Forest Service Research Paper INT-69. 20 pp.

__________. 1974. Appraising Forest Fuels: A Concept. USDA Forest Service Research Note INT-187. 10 pp.

__________. 1976. "Fuels - The Source of the Matter." In Air Quality and Smoke from Urban and Forest Fires Inter. Symp. pp. 318-21.

Appell, H.R., Y.C. Fu, E.G. Illig, F.W. Steffgen, and R.D. Miller. 1975. Conversion of Cellulosic Wastes to Oil. Bureau of Mines, Energy Research Center, Pittsburgh, Pennsylvania. 31 pp.

Appleby, R.W. 1970. "Thinning Slash and Fire Control." Fire Control Notes 31(1):8-10.

Arbogast, H.A. 1974. The Timber Resources of the Inland Empire Area, Washington. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station. USDA Forest Service Resource Bulletin PNW-50. Portland, Oregon. 56 pp.

Arnold, J. F. 1976. Federal Funds for Prescribed Burning. Presented to the Arizona Conservation Council. December 1. 3pp.

Arola, R.A. 1976. "Wood Fuels - How Do They Stack Up?" Proceedings of Energy and the Wood Product Industry. FPRS #P-76-14. pp. 34-45.

Austin, J.W. 1973. Fiberwood Use in Washington, Oregon and California, 1970-80. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Research Paper PNW-169. Portland, Oregon. 31 pp.

Auvil, Clifford J. 1973. Fire Environmental Test Chamber: Its Design and Development. USDA Forest Service. Pacific Southwest Forest and Range Experiment Station Research Note. Berkeley, California. 10 pp.

Ay, J.H. and M. Sichel. 1976. "Theoretical Analysis of NO Formation Near the Primary Reaction Zone in Methane Combustion." Combustion and Flame 25:1-15.

Ayer, H. and R. Kirkpatrick. 1970. "Where There's Smoke." ESSA 5(4):16-19. Rockville.

Baden, J.H.H. 1971. Prescribed Burning Plan 1972-1976 for the Fort Apache Indian Reservation. 11 pp.

Baker, G. 1977. ITF-FSU. November 10, 1977. Exhibit B.

Baker, A.J. and E.H. Clarke. 1976. "Wood Residue as an Energy Source - Potential and Problems." Proceedings of the Rocky Mountain Forestry Industry Conference. pp. 7-13.

Bare, B. Bruce and Brian F. Anholt. 1976. Selecting Forest Residue Treatment Alternatives Using Goal Programming. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-43. Portland, Oregon. 26 pp.

Bare, B. Bruce, Benjamin A. Jayne and Brian F. Anholt. 1976. A Simulation-Based Approach for Evaluating Logging Residue Handling Systems. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-45. Portland, Oregon. 30 pp.

Barger, R. 1972. Research and Development in the INT. USDA Forest Service. Close Timber Utilization Committee Report. pp. 62-69.

Barney, R.J. 1974. Wildfire Smoke Conditions: Interior Alaska. USDA Forest Service Research Paper PNW-178. 18 pp.

__________. 1975. "Fire Management: A Definition." J. For. 73(8):498-519.

Barnhart, F.T. 1978. "Communication: Up Slope Directional Filling." Timber Cutter: January-February.

Barrows, Jack S. 1974. "The Challenges of Forest Fire Management." Western Wildlands 1(3):3-5.

Bass, A., A.Q. Eschenroeder, and B.A. Egan. 1977. The Livermore Regional Air Quality Model (LIRAQ): A Technical Review and Market Analysis. ERT Report P-2348-1.

Bassett, P.M. 1977. Timber Resources of Southwest Oregon. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Resource Bulletin PNW-72. Portland, Oregon. 29 pp.

Bassett, P.M. and G.A. Choate. 1974. Timber Resource Statistics for Oregon - January 1, 1973. USDA Forest Service Resource Bulletin PNW-56.

__________. 1974. Timber Resource Statistics for Washington - January 1, 1973. USDA Forest Service Resource Bulletin PNW-53.

Beaufait, William R. 1965. Characteristics of Backfires and Headfires in Pine Needle Fuel Bed. USDA Forest Service Research Note INT-39.

Beaufait, William R. 1966. *Prescribed Fire Planning in the Int. West.* USDA Forest Service Research Paper INT-26.

________. 1968. *Scheduling Prescribed Fires to Alter Smoke Production and Dispersion*. S.W. Interagency Fire Council.

________. 1971. *Fire and Smoke in Montana Forests*. USDA Forest Service Report.

________. 1974. *Inventory of Slash Fuels Using 3P Subsampling*. USDA Forest Service General Technical Report INT-13. 17 pp.

Beaufait, William R. and Owen P. Cramer. 1969. *Prescribed Fire Smoke Dispersion Principles*. Division of Fire Control, Forest Service, Missoula, Montana. 12 pp.

Beaufait, William R. and W.C. Fischer. 1969. *Identifying Weather Suitable for Prescribed Burning*. USDA Forest Service Research Note INT-94.

Beaufait, William R., C.E. Hardy and W.C. Fischer. 1975. (Revised 1977.) *Broadcast Burning in Larch-Fir Clearcuts: The Miller Creek-Newman Ridge Study*. USDA Forest Service Research Paper INT-175. 53 pp.

Becker, D. 1973. "Mathematical Description of Forest Fire Emissions." In *Development of Emission Factors for Estimating Atmospheric Emissions from Forest Fires*. IIT Research Institute. Chicago, Illinois. NTIS PB-230-889.

Benner, W.H., P. Urone, C.K. McMahon, and P. Ryan. 1977. *Photochemical Potential of Forest Fire Smoke*. Presented at the 70th Annual Meeting of the Air Pollution Control Association. Toronto, Ontario, Canada.

Benson, R.E. 1974. *Lodgepole Pine Logging Residues, Management Alternatives.* USDA Forest Service. Intermountian Forest and Range Experiment Station Research Paper INT-160. 28 pp.

Benson, R.E. and R.A. Strong. 1977. *Wood Product Potential in Mature Lodgepole Pine Stands*. USDA Forest Service Research Paper INT-194. 16 pp.

Berger, J.M. 1968. *Timber Resource Statistics for Central Oregon*. USDA Forest Service Resource Bulletin PNW-24.

Berguall, J.A., D.C. Bullington and L. Gee. 1977. *1976 Washington Mill Survey*. State of Washington Mill Survey Series Report #5.

Bethlahmy, N. 1976. "Exposure, Clear Cutting, and Burning Affect Soil Moisture Levels." *Northwest Science* 50(3):140-45.

Biswell, Harold H. 1973. "A Summary of Research on Smoke and Air Pollution from Forest and Wildland Burning." In *Proceedings of the 17th Annual Arizona Watershed Symposium*. pp. 28-33.

________. 1976. "Problems of Prescribed Burning and Smoke in Wildland - Urban Areas of California." In *Air Quality and Smoke from Urban and Forest Fires Inter. Symp*. National Academy of Sciences. p. 247.

Biswell, Harold H. and James K. Agee. 1973. *Prescribed Fire Effects on Water Repellency, Infiltration and Retention in Mixed-Confier Litter, Duff and Soil*. School of Forestry and Conservation, California Univ., Berkeley, Technical Completion Report. 8 pp.

Biswell, Harold H., H.R. Kallander, R. Komarek, R.J. Vogl and H. Weaver. 1973. *Ponderosa Fire Management*. Misc. Publ. #2. Tall Timbers Research Station. Tallahassee, Florida. p. 49.

Bjornsen, R.L. 1976. "Meteorological Needs for Fire Management Planning." In *Proceedings of the Fourth National Conference on Fire and Forest Meteorology*. November 16-18, 1976. St. Louis, Missouri. USDA Forest Service General Technical Report RM-32. pp. 42-43.

Blackman, T. 1978a. "Bark Pellets Are High-Energy Fuel for Coal, Gas Applications." *For. Indus*. 105(2):48-49.

________. 1978b. "Crude Oil from Wood Chips? Test Plant Shows It's Possible." *For. Indus*. 105(2):50-51.

Blumer, M. and W.W. Youngblood. 1975. "Polycyclic Aromatic Hydrocarbons in Soils and Recent Sediments." *Science* 188:53-5.

Bolsinger, C.L. 1969. *The Timber Resources of the Olympic Peninsula, Washington*. USDA Forest Service Resource Bulletin PNW-31.

________. 1971a. *Changes in Commercial Forest Area in Oregon and Washington, 1945-70*. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station.

________. 1971b. *Timber Resources of the Puget Sound Area*. USDA Forest Service Resource Bulletin PNW-36.

________. 1975a. *The Timber Resources of the Blue Mountain Area, Oregon*. USDA Forest Service Resource Bulletin PNW-57.

________. 1975b. *Timber Resources and the Timber Economy of Okanogan County, Washington*. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Resource Bulletin PNW-58. Portland, Oregon. 32 pp.

Boubel, R.W. 1968. Particulate Emissions from Sawmill Waste Burners. Corvallis, Oregon Engineering Experimental Station Bulletin 42. Presented at 61st Annual Meeting of the Air Pollution Control Association.

________. 1977. "There's a Price to Pay for Clean Air, Prof Says." Gazette Times, November 7, 1977, Corvallis, Oregon.

Boubel, R.W., E.F. Darley and E.A. Schuck. 1969. "Emissions from Burning Grass Stubble and Straw." Journal of the Air Pollution Control Association 19:497-500.

Bradley, E. 1977. ITF-FSU. November 10, 1977. Exhibit E.

Brender, E.V. and R.W. Cooper. 1968. "Prescribed Burning in Georgia's Piedmont Loblolly Pine Stands." J. of For. 66(1).

Brender, Ernest V. and Hugh E. Mobley. 1974. "Regulations on Prescribed Burning and Air Quality." Forest Farmer 33(4):10.

Briggs, G.A. 1969. Plume Rise. Air Resources Atmospheric Turbulence and Diffusion Laboratory. ESSA. Oak Ridge, Tennessee.

________. 1975. "Plume Rise Predictions." Paper Presented at American Meteorological Society Workshop on Meteorology and Environment Assessment. Boston, Massachusetts. September 29 - October 3, 1975.

British Columbia Forest Service. 1969. A Guide to Broadcast Burning of Logging Slash in British Columbia. Forest Protection Handbook Series 2. Forest Protection Division, Victoria, B.C. 24 pp.

Brotak, E.A. and W.E. Reifsnyder. 1977. "An Investigation of the Synoptic Situations Associated with Major Wildland Fires." J. of Applied Meteorology 16(9):867-70.

Brown, G.W. 1971. "Clear Cut Logging and Sediment Problems in the Oregon Coast Range." Wat. Resources Res. 7(5):1189-98.

Brown, G.W., A.R. Gahler, and B.R. Marston. 1973. "Nutrient Losses After Clear-Cut Logging and Slash Burning in the Oregon Coast Range." Water Resources Res. 9(5):1450-53.

Brown, James K. 1970a. Physical Fuel Properties of Ponderosa Pine Forest Floors and Cheat Grass. USDA Forest Service Research Paper INT-74.

Brown, James K. 1970b. Vertical Distribution of Fuel in Spruce-Fir Logging Slash. USDA Forest Service Research Paper INT-81. 9 pp.

________. 1972. Field Test of a Rate-of-Fire-Spread Model in Slash Fuels. USDA Forest Service Research Paper INT-116. Ogden, Utah. 24 pp.

Brown, James K. 1974a. Handbook for Inventorying Downed Woody Material. USDA Forest Service General Technical Report INT-16.

__________. 1974b. Reducing Fire Potential in Lodgepole Pine by Increasing Timber Utilization. USDA Forest Service. Intermountain Forest and Range Experiment Station Research Note INT-181. 6 pp.

Brown, J.K., J.A. Kendall-Snell and D.L. Burnell. 1977. Handbook for Predicting Slash Weight of Western Conifers. USDA Forest Service General Technical Report INT-37.

Browne, F.L. 1963. Theories of the Combustion of Wood and Its Control (Revised). Forest Prod. Lab. Publication No. 2136. 69 pp.

Bryan, G.M. and R.E. Martin. 1970. "The Modeling of Fire Whirlwinds." For. Science. 16(4):386-99.

Bryan, Richard W. 1977. "Weyerhaeuser Arkansas Operation Firmly Wedded to Whole Tree Chippping." Forest Industries 104(9):42-43.

Buchman, R.E. 1975. Forest Residues Program: Research, Development and Applications Charter. USDA Forest Service PNW FRES.

Buongiorno, J. and R.A. Oliveira. 1977. "Growth of the Particleboard Share of Production of Wood-Based Panels in Industrialized Countries." Can. J. of For. Res. 7(2):383-91.

Burckle, J.O. and J.A. Dorsey. 1968. Air Pollution and Open Burning in Forestry Operations. Presented at Joint Meeting of Southern Fire Chiefs and Information and Education Chiefs, Houston, Texas, June 10-14. Preprint available from Public Health Service, National Center for Air Pollution Control, Cincinnati, Ohio. 14 pp.

Burwell, D. 1977a. Relationships of Uphill Felling on Logging and Forest Practices in the Douglas-Fir Region. Interim Task Force on Forest Slash Utilization, Forest Management Committee. Exhibit G. October 12, 1977.

__________. 1977b. Some Economic and Silvicultural Aspects of PUM in Relation to Oregon's Smoke Management Program. Interim Task Force on Forest Slash Utilization, Forest Management Committee. Exhibit H. October 12, 1977.

__________. 1977c. ITF-FSU. November 10, 1977. Exhibit A.

California Energy Resources Conservation and Devlopment Committee. 1977. *Agricultural Waste Gasification Project*. p. 3.

Camran Corp., The. 1974. *A Proposal for Resource Recovery of Logging Wastes in the Region X Area*.

Carroll, J.J. et al. 1977. "The Dependence of Open Field Burning Emissions and Plume Concentrations on Meteorology, Field Conditions and Ignition Techniques." *Atmos. Envir*. 11:1037-50.

Cavender, J.H., D.S. Kircher and A.J. Hoffman. 1973. *Nationwide Air Pollutant Emission Trends, 1940-1970*. Environmental *Protection Agency. Research Triangle Park, North Carolina*. 52 pp.

Chandler, Craig C. 1976. "Meteorological Needs of Fire Danger and Fire Behavior." In *Proceedings of the Fourth National Conference on Fire and Forest Meteorology*. *November 16-18, 1976. St. Louis, Missouri. USDA Forest Service General* Technical Report RM-32. pp. 38-41.

Chavasse, C.G.R. 1975. "Objectives, Management and Effects of Forest Burning." *Proceedings of the 1975 Clean Air Conference*. The Clean Air Society *of Australia and New Zealand, February 17-21*, 1975. pp. 92-113.

Charleson, R.J. 1968. "Atmospheric Aerosol Research at the University of Washington." *Journal of the Air Pollution Control Association* 18:652-54.

Chi, C.T. and D.L. Zanders. 1977. *Source Assessment: Agricultural Open Burning, State-of-the-Art.* Unpublished draft document. EPA *Contract Number 600/2-77-107a.*

Christensen, G.W. 1975. "Wood Residue Sources, Uses, and Trends." *Proceedings of Wood Residue as an Energy Source*. FPRS #P-75-13. *pp. 39-41.*

Clairborne, Robert. 1972. "When It's Natures Way, Forest Fires are a Benefit." *Smithsonian* 3(2):16.

Clarke, E.H. 1976. *Research and Development in the Pacific Northwest. Close Timber Utilization Committee Report. USDA Forest Service.* pp. 55-61.

__________. 1976. "Residue Research - Recent Developments." *Proceedings of Annual Meeting*. Northwest Forest Fire Council. *pp. 80-85*.

Clarke, E.H. and J.W. Henley. 1978. "Unused Mill Residuals May All Serve as Fuel." *For. Indus*. 105(2):54-55.

Cleary, B.D. 1977. *Field Notes of Site Preparation Techniques in Use.* Personal Communication: Oregon State University Extension Service.

Close Timber Utilization Committee. 1972. Report. USDA Forest Service Washington.

Close Timber Utilization Work Conference. 1976. *1975 Proceedings of U.S. Forest Products Laboratory, Madison, Wisconsin.* Limited Distribution.

Cole, B.L. 1977. *Selected Laws Administered by Department of Natural Resources.*

Coleman, Robert D. 1976. "Ambient Air Quality Standards for Particulate Matter in the United States" in *Air Quality and Smoke from Urban and Forest Fires International Symposium.* October 24-26, 1973. Washington, D.C. National Academy of Sciences. pp. 162-69.

Connaughton, Charles A. 1969. "Fire Control." *Forest Service Manual*, Supplement 44, Region 6, Portland, Oregon. 17 pp.

__________. 1972. "Forest Fires Damage More Than Trees." *American Forests* 78(8):30.

Cooke, J.P. 1978. "Effect of Forest Burning Practices in Western Oregon and Washington on Air Quality East of the Cascades." Private communication with supporting documents.

Cooper, Charles F. 1971. "Effects of Prescribed Burning on the Ecosystem." *Prescribed Burning Symp. Proc.* April 14-16, 1971. Charleston, S.C. pp. 152-60.

Cooper, Robert W. 1971. "Pros and Cons of Prescribed Burning in the South." *Forest Farmer* 31(2):10.

__________. 1972. "Prescribed Burning - Why It is a Vital Forest Management Tool." *Forest Farmer* 31(7):218.

__________. 1974. "Status of Prescribed Burning and Air Quality in the South." *13th Proceedings of the Tall Timbers Fire Ecology Conference.* pp. 309-315.

__________. 1975. "Prescribed Burning." *J. Forestry* 73(12):776-80.

__________. 1976. "Trade-Offs Between Smoke from Wild and Prescribed Forest Fires." In *Air Quality and Smoke from Urban and Forest Fires Intern. Symp.* National Academy of Sciences. p. 19.

Cooper, Robert W. and A.T. Altobellis. 1969. "Fire Kill in Young Loblolly Pine." *Fire Control Notes* 30(4):14-15.

Corder, S.E. and G.H. Atherton. 1970. "Wood and Bark Residue Disposal in Wigwam Burners." Bull. Ore. For. Res. Lab #11, p. 68.

Core, J. 1977. ITF-FSU. November 10, 1977. Exhibit H.

Cornell, B.L et al. 1977. Soil Compaction Study Task Force Report. USDA Forest Service. Regions 5 and 6.

Countryman, C.M. 1964. "Mass Fires and Fire Behavior." USDA Forest Service. Pacific Forest and Range Experiment Station Resource Paper PSW-19. Berkeley, California.

________. 1971. Fire Whirls ... Why, When and Where. USDA Forest Service. PSW-F&RES,

Countryman, C.M. and M.H. McCutchan. 1969. Fire Weather and Fire Behavior at the 1968 Canyon Fire. USDA Forest Service Research Paper PSW-55.

Craft, E. Paul. 1976. Utilizing Hardwood Logging Residue, A Case Study in the Appalachians. USDA Forest Service. Northeastern Forest Experiment Station Research Note NE-230. Upper Darby, Illinois. 7 pp.

Craig, C. and M. Wolf. 1977. "A Status Report on the Verification of the LIRAQ, Model and Complex Terrain Model by the OSU Air Resource Center." Personal Communication.

Craig, James B. and Irene McManus. 1972. "Fire in the Environment." American Forests 78(8):24.

Cramer, Owen P. 1959. Relation of Number and Size of Fires to Fire-Season Weather Indexes in Western Washington and Oregon. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Research Note 175. Portland, Oregon. 11 pp.

________. 1969. Disposal of Logging Residues Without Damage to Air Quality. USDC, Environmental Sci. Serv. Admin. Technical Memo WBTM WR-37.

________. 1972. "Potential Temperature Analysis for Mountainous Terrain." J. Appl. Meteorol. 11(1):44-50.

________. 1974. "Air Quality Influences." In Environmental Effects of Forest Residues Management in the Pacific Northwest - A State-of-Knowledge Compendium. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Report PNW-24. Portland, Oregon. 52 pp.

Cramer, Owen P. and Howard E. Graham. 1971. "Cooperative Management of Smoke from Slash Fires." J. Forestry 69(6):327-331.

Cramer, Owen P. and S.G. Pickford. 1973. "Factors Influencing Smoke Management Decisions in Forest Areas." In Air Quality and Smoke from Urban and Forest Fires Inter. Symp. National Academy of Sciences.

Cramer, Owen P. and James N. Westwood. 1970. Potential Impact of Air Quality Restrictions on Logging Residue Burning. USDA Forest Service. Pacific Southwest Forest and Range Experiment Station Research Paper PSW-64. Berkeley, California. 12 pp.

Crow, A.B. 1975. "Fire: A Silvicultural Tool in Southern Forestry." Proceed. Soc. Amer. For. Conv. pp. 95-101.

Currier, R.A. 1972. "An Assessment of Current Bark Utilization Opportunities." Proceedings of the 27th Northwest Wood Prod. Clinic.

__________. 1977. Manufacturing Densified Wood and Bark Fuels. Oregon State University Extension Service Special Report #490.

Currier, R.A. and M.L. Laver. 1972. Utilization of Bark Waste. Terminal Progress Report. EPA Grant #R-EP 00276-04. NTIS PB-221 876.

__________. 1973. Utilization of Bark Waste. Oregon State Univ., Corvallis, Department of Forest Products. Final Report. 184 pp.

Cushwa, C.T. and M. Hopkins. 1970. Responses of Legumes to Prescribed Burns in Loblolly Pine Stands of the South Carolina Piedmont. USDA Forest Service Research Note SE-140.

Dana, M.T., et al. *Precipitation Scavenging of Fossil-Fuel Effluents.* Publ. #EPA-600/4-76-031. p. 94.

Darley, Ellis F. 1971. "Burning Agricultural Wastes and Effects on Agriculture. *Symposium Proceedings Agric. and the Environment in Southern San Jose Valley, California.* Division of Agricultural Science, University of California. pp. 17-24.

———. 1976. *Emission Factor Development for Leaf Burning.* Office of Air Quality Planning and Standards. U.S. Environmental Protection Agency. NTIS PB-263-660. EPA Report No. EPA/405/3-76/044.

———. 1977. *Emission Factors from Burning Agricultural Wastes Collected in California.* Final Report CAL/ARB, Project 4-001. Statewide Air Pollution Research Center, University of California.

Darley, Ellis F. and H.H. Biswell. 1973. "Air Pollution from Forest and Agricultural Burning." *J. Fire and Flammability* 4(4):74-81.

Darley, E.F. and S.L. Lerman. 1975. *Air Pollutant Emissions from Burning Sugar Cane and Pineapple Residues from Hawaii.* U.S. Environmental Protection Agency Publication #450/3-75-071.

Darley, Ellis F., F.R. Burleson, E.H. Mateer et al. 1966. "Contribution of Burning of Agricultural Wastes to Photochemical Air Pollution." *J. Air Pollution Control Assoc.* 16(12):685-90.

Darley, Ellis F. et al. 1974. *Air Pollution from Forest and Agricultural Burning.* California Air Resources Board Project 2-017-1. University of California, Davis, California.

Darley, E.F., S. Lerman, G.E. Miller, Jr. and J.F. Thompson. 1976. "Laboratory Testing for Gaseous and Particulate Pollutants from Forest and Agricultural Fuels." In *Proceedings of International Symposium on Air Quality and Smoke from Urban and Forest Fires.* National Academy of Sciences. Washington, D.C.

Davis, L.S. and R. W. Cooper. 1963. "How Prescribed Burning Affects Wildfire Occurrence." *J. of For.* 61(12).

Dawson, George and Ogden Lazenby. 1972. "Effects of Fire on the Environment." *American Biology Teacher* 34(5):269.

Debell, D.S. and C.W. Ralston. 1970. "Release of Nitrogen by Burning Light Forest Fuels." *Proc. Soil Sci. Soc. Amer.* 34(6):936-38.

DeByle, Norbert V. 1973. "Broadcast Burning of Log Residue and the Water Repellency of Soils." *Northwest Sci.* 47(2):77-87.

———. 1976. "Fire, Logging, and Debris Disposal Effects on Soil and Water in Northern Coniferous Forests." *Proceedings of the 16th International Union of Forestry Research Organizations.* Oslo, Norway. Volume 1, pp. 201-212.

Deeming, J.E. 1975. "Fuel Models in the National Fire Danger Rating (NFDR) System." J. For. 73(6):347-50.

_________. 1976. The National Fire Danger Rating System - Latest Developments. USDA Forest Service General Technical Report RM-32.

Deeming, J.E. and J.W. Lancaster. 1972. National Fire Danger Rating System. U.S. Fire Service Research Paper RM-84.

_________. 1972. National Fire Danger Rating System (Revised). USDA Forest Service Research Paper RM-84.

DelBel, Elsio, Sam Friedman, Paul M. Yavorsky and Henry H. Ginsberg. 1975. "Design of a Wood Waste-to-Oil Pilot Plant." Am. Chem. Soc., Div. Fuel Chem. Meeting, Philadelphia, Pa., April 6-11, 1975. Volume 20, Number 2. pp. 17-21.

Dell, John D. 1967. Remote Ignition of Logging Slash. USDA Forest Service Research Note PSW-154. 2 pp.

_________. 1976a. Fuel Management Training Guidelines for National Forests in the Pacific Northwest Region. USDA Forest Service Region 6.

_________. 1976b. "Fuels and Fire Management...Prescribed Fire Use on the National Forests in the Pacific Northwest Region." Proceed. of the 1976 Tall Timbers Fire Ecology Conf. #15. pp. 119-125.

_________. 1977a. Action Plan for Improved Slash Burning Programs on Westside National Forests in Region 6. USDA Forest Service Region 6.

_________. 1977b. "Hazard Accumulation - Risks and Mitigation." Unpublished transcript.

_________. 1977c. "Some Implications of Eliminating Prescribed Burning as a Treatment Option in Managing Forest Vegetation and Fuels in the Pacific Northwest." R-6 Fuel Mgmt. Notes 5(2):1-10.

_________. 1977d. A Status Report on Potential Use of Forest Residues for Energy Production. USDA Forest Service Region 6.

Dell, John D. 1977e. Forest Residue Treatment - Methods, Cost and Limitations. USDA Forest Service PNW. ITF-FSU, Exhibit D.

_________. 1977f. ITF-FSU. November 10, 1977. Exhibit C.

Dell, John D. and L.R. Green. 1968. "Slash Treatment in the Douglas-Fir Region - Trends in the Pacific Northwest." J. For. 66(8):610.

Dell, John D. and G.I. Schram. 1970. "Oscillating Sprinklers Backup for Burnout." Fire Control Notes 31(2):8-10.

Dell, John D.,and Franklin R. Ward. 1971. Logging Residues on Douglas-fir Region Clearcuts - Weights and Volumes. USDA Forest Service Pacific Northwest Forest and Range Experiment Station Resource Paper PNW-115. Portland, Oregon. 14 pp.

________. 1969. Reducing Fire Hazard in Ponderosa Pine Thinning Slash by Mechanical Crushing. USDA Forest Service Resource Paper PSW-57.

Dell, John D., Franklin R. Ward and Robert E. Lynott. 1970. Slash Smoke Dispersal Over Western Oregon . . . A Case Study. USDA Forest Service. Pacific Southwest Forest and Range Experiment Station Resource Paper PSW-67. Berkeley, California. 9 pp.

Dickerhoof, H.E. 1976. "Particleboard Production, Markets and Raw Materials in the United States." For. Prod. J. 26(10):16-20.

________. 1977. "Particleboard Production, Markets and Raw Material Use in Western U.S. Surveyed by USDA." Plywood and Panel. February. (Reprint)

Dickman, A. 1978. "Reduced Fire Frequency Changes Species Composition of a Ponderosa Pine Stand." J. For. 76(1):24-25.

Dietrich, John H. 1971. "Air Quality Aspects of Prescribed Burning." Proc. of Belle W. Baruch Research Inst. in Forestry, Wildlife Science, and Marine Biology, Prescribed Burning Symp. Charleston, S.C., April 14-16, 1971. pp. 139-151.

________. 1976. "Prescribed Burning in Ponderosa Pine - State of the Art." Presented in Region 6, Eastside Prescribed Fire Workshop. USDA Forest Service.

Dillon, J.C. 1970. "We Should Treat Forest Fires as a Major Pollution Cause." Canadian Pulp and Paper Indus., Toronto 23(5):53.

Dodge, M. 1972. "Forest Fuel Accumulation - A Growing Problem." Science 177(4044):139-41.

Dodge, M. and J.L. Davis. 1966. "Fire-Retardant Chemicals - An Aid to Slash Disposal." J. For. 64(2):98.

Donoghue, L.R. and V.J. Johnson. 1975. Prescribed Burning in the North Central States. USDA Forest Service Research Paper NC-111.

Dow Chemical U.S.A. 1977. Miscellaneous Information on Tordon 101.

Dowdle, B. 1973. Logging Waste Disposal on Western National Forests. University Institute of Governmental Research. Washington Public Policy Notes, Volume 1, No. 3. Seattle, Washington.

________. 1977. "Slash Disposal Requirements Analyzed." For. Indust. 101(5):44-45.

Draxler, Roland R. 1977. A Mesoscale Transport and Diffusion Model. NOAA Tech. Memo ERL ARL-64. p. 31.

Dyrness, C.T. 1973. "Early Stages of Plant Succession Following Logging and Burning in the Western Cascades of Oregon." Ecology 54(1):57-69.

Dyrness, C.T. and C.T. Youngberg. 1957a. Some Effects of Logging and Slash Burning in Physical Soil Properties in the Corvallis Watershed. USDA Forest Service Research Paper PNW-19. Pacific Northwest Forest and Range Experiment Station. 15 pp.

_________. 1957b. "The Effect of Logging and Slash-Burning on Soil Structure." Proc. Soil Soc. of Amer. 21(4):444-47.

Eagan, R.C., P.V. Hobbs, and L. F. Radke. 1974. "Measurements of Cloud Condensation Nuclei and Cloud Droplet Size Distributions in the Vicinity of Forest Fires." J. of Applied Meteorology 13:553-57.

"East Winds Have Had a Big Effect on Oregon Forestry." Forest Log 41(3):4.

Eccleston, A.J., N.K. King and D.R. Packham. 1974. "The Scattering Coefficient and Mass Concentration of Smoke from Some Australian Forest Fires." J. Air Pollution Control Assoc. 24(11):1047-50.

Ellis, T. H. 1975a. "Should Wood Be a Source of Commercial Power?" Forest Products J. 25(10):13-16.

_________. 1975b. "The Role of Wood Residue in the National Energy Picture." Proceedings of Wood Residue As an Energy Source. FPRS #P-75-13. pp. 17-20.

_________. 1976. "How Wood Residues Can Help National Energy Needs." Wood and Wood Products 81(4):52-53.

_________. The Role of Wood Residue in the National Energy Picture. USDA Forest Service. For. Prod. Lab. (Reprint)

Elmgren, R.C. 1977. Factors That Encourage or Discourage More Complete Residue Utilization. Interim Task Force on Forest Slash Utilization. Forest Management Subcommittee, Exhibit E.

Endeau, F. 1974. Prescribed Fire to Regenerate Subalpine Lodgepole Pine. Inf. Rep. Northern For. Res. Centre, Canada. NOR-X-114. 17 pp.

Endeau, F. and W.D. Johnstone. 1974. Prescribed Fire and Regeneration on Clearcut Spruce-Fir Sites in Foothills of Alberta. Info. Rep. Northern Res. Centre, Canada. NOR-X-126. 33 pp.

Erickson, John R. 1975. "The Harvesting of Forest Residues." Amer. Inst. of Chem. Eng. 71(146):27-29.

Evans, R.S. 1973. Hogged Wood and Bark in British Columbia Landfills. Western Forest Products Lab. Report No. VP-X-118. Vancouver, British Columbia.

Evans, L.F., N.K. King, D.R. Packham and E.T. Stephens. 1974. "Ozone Measurements in Smoke from Forest Fires." Environ. Sci. and Tech. 8(1):75-76.

Evans, L.F., I.A. Weeks et al. 1977. "Photochemical Ozone in Smoke from Prescribed Burning of Forests." Environ. Sci. and Tech. 11(9):896-900.

Fabrick, A., R. Sklarew and J. Wilson. 1977. Point Source Model Evaluation and Development Study. Science Applications, Inc. NTIS #PB 271 646. Pp. 197.

Fahnenstock, G.R. 1968. Fire Hazard from Precommercial Thinning of Ponderosa Pine. USDA Forest Service Research Paper PNW-57.

_________. 1968. Problem Analysis: Impacts of Forest Residues and Their Disposal on Forest Land Management and Environment in the Pacific Northwest. USDA PNW. Inhouse Publication #4050-1.

_________. 1970. Two Keys for Appraising Forest Fire Fuels. USDA Forest Service Research Note PNW-99.

_________. 1973. "Use of Fire in Management of Forest Vegetation." Trans. of ASSAE 16(3):410-13, 419.

_________. 1974a. "Fires, Fuels and Flora as Factors in Wilderness Management: The Pasayten Case." Proceedings of the Tall Timbers Fire Ecology Conference. October 16-17, 1974. Tall Timbers Research Station, Portland, Oregon, PNW-15.

_________. 1974b. The Value of Fire in Management of the Forests of the Inland West. 62 pp.

Farnsworth, E. 1977. "Old/New Way to Handle Wood Waste - Densify It." Wood and Wood Products: November. p. 23.

Fawcett, Edwin B. 1976. "Current Capabilities in Prediction at the National Weather Service's National Meteorological Center." In Proceedings of the Fourth National Conference on Fire and Forest Meteorology. USDA Forest Service Genertal Technical Report RM-32. pp. 12-19.

Feldstein, M., D. Duckworth, H.C. Wohlers and B. Linsky. 1963. "The Contribution of the Open Burning of Land Clearing Debris to Air Pollution." J. Air Pollution Control Assoc. 13(11):542-46.

Fenn, R.W. 1976. "Optical Properties of Aerosols." Handbook on Aerosols (R. Dennis, ed.). NTIS #TID-26608. pp. 66-92.

Fennelly, Paul F. 1976. "The Orighin and Influence of Airborne Particulates." American Scientist 64(1):46.

Finklin, A.I. 1973. Meteorological Factors in the Sundance Fire Run. USDA Forest Service General Technical Report INT-6.

"Fire in Wildland Management." J. For. 71:624-49.

Fire Management Center. 1975. Prescribed Burning Report. For Apache Agency.

Fischer, W.C. and C.E. Hardy. 1976. *Fire-Weather Observer Handbook*. USDA Forest Service Agr. Handbook #494. 152 pp.

Flaherty, David C. 1972. "Are We Objective About Forest Fires?" *American Forests* 78(8):12.

Folkman, W.S. 1975. *Butte Country, California Residents: Their Knowledge and Attitudes About Forest Fires Reassessed*. USDA Forest Service Res. Note PSW-297.

Forest Fuels, Inc. *Wood/Gas Industrial Generator Burner System*. Bulletin #1176.

Fosberg, Michael A. 1966. *Some Characteristics of the Three-Dimensional Structure of Santa Ana Winds*. USDA Forest Service Research Paper PSW-30.

__________. 1971a. *Derivation of the 1- and 10-Hour Time Lag Fuel Moisture Calculations for Fire Danger Rating*. USDA Forest Service Research Note RM-207.

__________. 1971b. *Fine Herbaceous Fuels in Fire-Danger Rating*. USDA Forest Service Research Note RM-185.

__________. 1975. *Heat and Water Vapour Flux in Conifer Forest Litter and Duff: A Theoretical Model*. USDA Forest Service Research Paper RM-152. 23 pp.

__________. 1976a. "New Technology for Determining Atmospheric Influences on Smoke Concentrations." In *Air Quality and Smoke from Urban and Forest Fires Inter. Symp*. National Academy of Sciences. p. 148.

__________. 1976b. *Estimating Airflow Patterns Over Complex Terrain*. USDA Forest Service Research Paper RM-162.

Fougler, A.N., Frank Freese and Joan E. Lengel. 1976. *Solid Wood Content of Western Softwood Logging Residues*. Forest Products Lab. Research Paper FSRP-FPL-253. Madison, Wisconsin. 9 pp.

Franklin, J.F. and C.T. Dryness. 1973. *Natural Vegetation of Oregon and Washington*. USDA-FS General Technical Report. PNW-8. pp. 417.

Fredriksen, R.L. 1971. "Comparative Chemical Water Quality - Natural and Disturbed Streams Following Logging and Slash Burning." *Proceedings of a Symposium: Forest Land Uses and Stream Environment*. pp. 125-137.

Freeburn, S. 1977. *ITF-FSU*. November 10, 1977. Exhibit F.

French, R.E. 1975. *Forest Burning and Smoke Management*. Bureau of Indian Affairs. Portland, Oregon.

Fritschen, L. 1967. "Air Quality and the Use of Fire for Forest Land Management, Current Research." *58th Western Forest Conf. Proc.* Western Forest and Conservation Assoc., Portland, Oregon.

Fritschen, L., Harley Bovee, Konrad Buettner, Robert Charlson, Lee Monteith, Stewart Pickford, James Murphy and Ellis Darley. 1970. *Slash Fire Atmospheric Pollution.* Pacific Northwest Forest and Range Experiment Station and California Univ., Riverside, Statewide Air Pollution Research Center RP-PNW-97. 42 pp.

Fritschen, L. and C.H. Driver. 1969. *Dispersion of Air Tracers Into and Within a Forested Area.* Parts 1 and 3. U.S. Army Atmospheric Sciences Laboratory. Univ. of Washington Grant DA-AMC-28-043068-G8.

Fuller, W.H. 1966. "New Organic Pelleted Compost." *Compost Science*: Autumn-Winter. p. 30.

Fuyaev, V.V. 1975. "Research on the Effects of Fires and the Application of Fire in Forestry." *Trans., Env. Canada* #00ENV TR 936. 33 pp.

Gagnon, S. 1977. ITF-FSU. Exhibit O. November 10, 1977.

Galbraith, Marlin C. 1972. "Effect Timber Harvest and Use of Logging Residues." Env. Affairs 2(2):314.

Gardner, R.B. and D.F. Gibson. 1974. Improved Utilization and Disposal of Logging Residues. Presented at the 1974 Winter Meeting of the American Society of Agricultural Engineers.

Gardner, R.B. and D.W. Hann. 1972. Utilization of Lodgepole Pine Logging Residues in Wyoming Increases Fiber Yield. U.S. Forest Service. Intermountain Forest and Range Experiment Station Research Note INT-160. 6 pp.

Gedney, D.R., D.D. Oswald and R.D. Fight. 1975. Two Projections of Timber Supply in the Pacific Coast States. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Resource Bulletin PNW-60. 40 pp.

Gerstle, R.W. and D.A. Kemnitz. 1967. "Atmospheric Emission from Open Burning." J. Air Pollution Control Assoc. 17(5):324-27.

Getz, Dale. 1975. "Something New is Slash Disposal." Fire Management 34(4):14-15.

Gipe, D. 1974. "Response of Range to Burning." In Proceedings of Tall Timber Fire Ecology Conference. October 16-17, 1974. Tall Timbers Research Station. Portland, Oregon. PNW-15.

Goldy, D.L. 1977. ITF-FSU. November 7, 1977. Exhibit C.

Golson, R.E. and J.P. Mohler. 1975. PORTAPIT Test Report. Washington Dept. of Natural Resources Note 11.

Gould, N. 1972. Alternative Sales Arrangements. Close Timber Utilization Committee Report. USDA Forest Service. pp. 29-31.

Graham, H.E. 1953. "The Columbia Gorge Wind Funnel." Weatherwise, August, pp. 104-107.

Graham, J.K. 1974. Feasibility Study of a Logging Residue Chip Mill. Gram Development Co., Portland, Oregon. 11 pp.

Grantham, J.B. 1978. "Wood's Future Seems Directed to Energy Ahead of Chemicals." For. Indus. 105(2):52-53.

________. 1974. Status of Timber Utilization on the Pacific Coast. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-29. Portland, Oregon. 42 pp.

Grantham, John B. 1974. "Forest Residue: A Forgotten Source of Energy." Paper Process. 10(2):17-20.

__________. 1976. "Energy Potential of Forest Residue." Proceedings of the NW Forest Fire Council Annual Meeting. USDA Forest Service.

Grantham, John B. and Thomas H. Ellis. 1974. "Potentials of Wood for Producing Energy." J. For. 72(9):552-556.

Grantham, John B., E.M. Estep, J.M. Pierovich, H. Tarkow, and T.C. Adams. 1974. Energy and Raw Material Potentials of Wood Residue in the Pacific Coast States - A Summary of a Preliminary Feasibility Investigation. USDA Forest Service. Intermountain Forest Range Experment Station General Technical Report INT-18. 37 pp.

Green, H.L. et al. 1964. Particulate Clouds, Dusts, Smokes and Mists. London. 2nd Edition. 471 pp.

Grier, C.C. and D.W. Cole. 1971. "Influence of Slash Burning on Ion Transportation in a Forest Soil." Northwest Sci. 45(2):100-106.

Habeck, J.R. and R.W. Mutch. 1973. "Fire Dependent Forests in the Northern Rocky Mountains." *Quaternary Research*, Vol. 3, No. 3. University of Washington. pp. 408-424.

———. 1975. "Forest and Forestry." *McGraw-Hill Yearbook of Science and Technology*. 4 pp.

Haines, D.A. and G.H. Updike. 1971. *Fire Whirlwind Formation Over Flat Terrain*. USDA Forest Service Research Paper NC-71. 12 pp.

Halak, B. 1977. "COFI Backing Gasification Project." *British Columbia Lumberman*: August. pp. 44-48.

Hall, E.H. 1977. "Comparison of Fossil and Wood Fuels." *Proc. of Energy and Wood Prod. Ind.* FPRS #P-76-14. pp. 141-45.

Hall, E.H., C.M. Allen, D.A. Ball, J.E. Burch and H.N. Cronkle. 1976. *Comparison of Fossil and Wood Fuels*. Industrial Environmental Research Lab., Research Triangle Park, N.C. EPA Final Task Report Number EPA/600/2-76/056. 254 pp.

Hall, Frederick C. 1971. "Fire Ecology." *Northwest For. Fire Counc. Ann. Meeting Proceed*. Portland, Oregon. pp. 7-11.

———. 1977. *Ecology of Natural Underburning in the Blue Mountains of Oregon*. USDA Forest Service. PNW Reg. Guide 51-1. 16 pp.

Hall, J. Alfred. 1970. *Wood, Pulp and Paper, and People in the Northwest.* USDA Forest Service. Pacific Northwest Forest and Range Experiment Station. Portland, Oregon. 34 pp.

———. 1972. *Forest Fuels, Prescribed Fire, and Air Quality*. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station. Portland, Oregon. 46 pp.

Hallock, T. 1977. *ITF-FSU*. November 17, 1977. Exhibit A.

Hallock, Wingard. 1977. *ITF-FSU*. November 7, 1977. Exhibit G.

Hamilton, T.E. et al. 1975. *Per-Acre Pricing - Its Effect on Logging Residue*. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Research Paper PNW-192. 7 pp.

Hammond, V.L., L.K. Mudge, C.H. Allen and G.F. Schiefelbein. 1974. "Energy from Forest Residuals by Gasification of Wood Wastes." *Pulp Pap.* 48(2):54-57.

Harkin, J.M. 1969. *Uses of Sawdust, Shavings and Waste Chips*. USDA Forest Service Research Note FPL-0208.

Harkin, J.M. and J.W. Rowe. 1971. *Bark and Its Possible Uses*. USDA Forest Servive Research Note FPL-091.

Harrison, R.T. 1975. *Slash . . . Equipment and Methods for Treatment and Utilization*. USDA Forest Service. ED&T Report 7120-7.

Harwood, C.E. and W.D. Jackson. 1975. "Atmospheric Losses of Four Plant Nutrients During a Forest Fire." *Australian Forestry* 38(2):92-99.

Hayes, G. Lloyd. 1941. *Influence of Altitude and Aspect on Daily Variations in Factors of Forest-Fire Danger*. USDA Circular #591.

Hazard, J.W. 1965. *Timber Resource Statistics for Southwest Washington*. USDA Forest Service. Resource Bulletin PNW-15.

Hazard, J.W. and M.E. Metcalf. 1965. *Forest Statistics for West Central Oregon*. USDA Forest Service Resource Bulletin PNW-10.

Hedin, A. and T. Turner. 1977. *What Is Burned in a Prescribed Fire?* Washington Department of Natural Resources Note 16.

Heebink, Bruce G. 1974. *Particleboards from Lodgepole Pine Forest Residue*. Forest Products Lab. Research Paper Number FSRP-FPL-221. Madison, Wisconsin. 16 pp.

Heinselman, Miron L. 1970. "The Natural Role of Fire in Northern Conifer Forests." *Naturalist* 21(4):14-23.

Hemeon, Wesley C.L. 1973. "A Critical Review of Regulation for the Control of Particulate Emissions." *J. Air Pollut. Control Assoc*. 23(5):376-87.

Hickerson, C.W. 1976. *Annual Fire Report, Region 6 (Pacific Northwest)*. USDA Forest Service. Fire and Aviation Management.

Hidy, G.M. and J.R. Brock. 1970. "An Assessment of the Global Sources of Tropospheric Aerosols." In *Second International Clean Air Congress*. Washington, D.C. Paper ME-26A.

Hobbs, P.V. and J.D. Locatelli. 1969. "Ice Nuclei from a Natural Forest Fire." *J. Applied Meteorology* 8:833-34.

Hobbs, P.V. and L.F. Radke. 1969. "Cloud Condensation Nuclei from a Simulated Forest Fire." *Science* 163:279-80.

Hobbs, P.V., L.F. Radke and S.E. Shumway. 1970. "Cloud Condensation Nuclei from Industrial Sources and Their Apparent Influence on Precipitation in Washington State." *J. Atmos. Sci*. 27:81-89.

Hodam, R. 1978. "Economical Energy Conversion Promised by Wood Gasification." For. Indus. 105(2):56-57.

Hoffman, A.J. (ed.). 1971. Nationwide Inventory of Air Pollutant Emissions, 1968. Division of Applied Technology Report AP-73. U.S. Environmental Protection Agency. Research Triangle Park, North Carolina. 36 pp.

Hooven, E.F. 1973a. "A Wildlife Brief for the Clearcut Logging of Douglas Fir." J. of Forestry. 71(4). (Reprint).

__________. 1973b. "Response of the Oregon Creeping Vale to the Clearcutting of a Douglas-Fir Forest." Northwest Science 47(4):256-64.

Hooven, E.F. and H.C. Black. 1976. "Effects of Some Clearcutting Practices on Small-Mammal Populations in Western Oregon." Northwest Science 550(4):189-208.

Host, J.R. and D.P. Lowery. 1970a. Portable Debarking and Chipping Machines Can Improve Forestry Practices. USDA Forest Service. Intermountain Forest and Range Experiment Station Research Note INT-112. 4 pp.

__________. 1970b. "Potentialities for Using Bark to Generate Steam Power in Western Montana." Forest Prod. J. 20(2):35-36.

Hough, Walter A. 1968. Fuel Consumption and Fire Behavior of Hazard Reduction Burns. Forest Service Research Paper SE-36. 7 pp.

__________. 1973a. "Prescribed Burning in South Surveyed, Analyzed." Fire Control Notes 34(1):4-5.

__________. 1973b. Fuel and Weather Influence Wildfires in Sand Pine Forests. USDA Forest Service Research Paper SE-106. 11 pp.

Houser, J. 1977. ITF-FSU. November 7, 1977. Exhibit E.

Howard, J.O. 1971. Volume of Logging Residues in Oregon, Washington and California...Initial Results from an 1969-70 Study. USDA Forest Service Research Note PNW-163.

__________. 1973. The Timber Resources of Central Washington. USDA Forest Service Resource Bulletin PNW-45.

__________. 1973. Logging Residue in Washington, Oregon and California: Volume and Characteristics. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Resource Bulletin PNW-44. Portland, Oregon. 26 pp.

Howath, H. and K.E. Noll. 1969. "The Relationship Between Atmospheric Light Scattering Coefficient and Visibility." *Atmospheric Environ*. 3:543-52.

Howlett, K. and A. Gamache. 1977. *Forest and Mill Residues - A Potential Source of Biomass Silvicultural Biomass Farms*, *Volume VI*. Mitre Corp. ERDA Contract Number EX-76-C-01-2081.

Howlett, M. 1972. *Equipment Development and Testing*. Close Timber Utilization Committee Report. USDA Forest Service. pp. 70-73.

Hurley, C. and D.J. Taylor. 1974. *Brown and Burn Site Preparation in Western Washington*. Washington Department of Natural Resources, DNR Note 8. Division of Forest Land Management Contribution 177. Olympia, Washington. 9 pp.

Inman, R.E. 1975. Evaluation of the Use of Agricultural Residues as an Energy Feedstock. Stanford Research Institute Semi-Annual Progress Report (July 1-December 31, 1974). Menlo Park, California. 89 pp.

________. 1977. Silvicultural Biomass Farms - Summary, Volume I. Mitre Corp. ERDA Contract Number E(49-18)-2081.

Ishibashi, Katsuji, Yoshio Noda, Shigeo Mitsui, and Masabumi Konya. 1973. "Production of Activated Carbon from Water Pulps." Hokkaido Kogyo Kaihatsu Shikensho Hokoku 8:128-37.

James, D.H. 1977a. *Sinslaw National Forest Smoke Management Guide*. USDA Forest Service Region 6.

__________. 1977b. *ITF-FSU*. November 10, 1977. Exhibit J.

James M. Montgomery, Inc. 1976. *Forest Harvest, Residue Treatment, Reforestation and Protection of Water Quality. Final Report.* EPA Region X. EPA Number EPA/910/9-76/020. Boise, Idaho. 280 pp.

Jamison, R.L. 1977. *The Forest as a Potential Source of Fuel for Energy.* Presented at the *Society of American Foresters Association Meeting*, October 3, 1977.

Jemison, G.M. and M.S. Lowden. 1974. *Management and Research Implications.* USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-24.

Jenne, D.E. 1975. *The Status of Air Quality in Benton, Franklin and Walla Wall Counties During 1975.* Benton-Franklin-Walla Wall Counties Air Pollution Control Authority.

Johansen, R.W. 1975. "Prescribed Burning May Enhance Growth of Young Slash Pine." *J. For.* 73(3):148-49.

Johansen, R.W., H.W. McNab, W.A. Hough and B.M. Edwards. 1976. "Fuels, Fire Behavior and Emissions." *Chapter IV, Southern Forestry Smoke Management Guidebook*. USDA Forest Service General Technical Report SE-10.

Johnson, A.H. 1974. "Fire History and Ecology, Lava Beds National Monument." *Proceedings Tall Timbers Fire Ecology Conference*. October 16-17, 1974. Tall Timbers Research Station, Portland, Oregon. PNW-15.

Johnson, L.R., G. Simmons and J. Peterson. 1977. *Unconventional Energy Sources*. Northwest Energy Policy Project. *Study Module III-B. Final Report.*

Johnson, Marion E. 1973. *Forest Products Pollution Control - Annotated Bibliography (Excluding Pulp and Paper).* Western Forest Products Lab. Information Report VP-X-100, Suppl. 1. Vancouver, British Columbia.

Johnson, Robert C. 1975. "Some Aspects of Wood Waste Preparation for Use as a Fuel." *TAPPI* 58(7):102-106.

Joint Interim Task Forces. 1977. *ITF-FSU*. November 7, 1977. Exhibit B.

Jones, D.A. 1973. "The Role of Prescribed Fire in Wildlife Management." *Proc. of the 17th Ann. Arizona Watershed Symp.*

Jorgensen, G. 1972. Alternative Sales Arrangements. Close Timber Utilization Committee Report. USDA Forest Service. pp. 32-37.

Jorgensen, J.R. and C.S. Hodges, Jr. 1970. "Microbial Characteristics of a Forest Soil after 20 Years of Prescribed Burning." Mycologia 62(4):721-26.

__________. 1971 "Effects of Prescribed Burning on the Microbial Characteristics of Soil." In Prescribed Burning Symposium Proceedings, April 14-16, 1971, Charleston, S.C. USDA Forest Service. pp. 107-14.

Junge, D.C. 1977. ITF-FSU. November 7, 1977. Exhibit D.

Jurgensen, M.F. and C.B. Davey. 1968. "Nitrogen-fixing Bluegreen Algae in Acid Forest and Nursery Soils." Canadian Journal of Microbiology 14:1179-83.

Kallander, H. 1969. "Controlled Burning on the Fort Apache Indian Reservation, Arizona." Tall Timbers Fire Ecology Conference. pp. 241-48.

Kalnis, A, I. Ievins, K. Abele, J. Pugulis and A. Kulkevics. 1975. "Drying of Green Wood and the Production of Vitamin Flour and Furfural from Logging Wastes." Kompleks. Mekhaniz. Rubok Ukhozda. pp. 95-104.

Karezyk, R.D. 1977. Forest Service Handbook. USDA Forest Service. Vancouver, Washington.

Kiil, A.D. 1971. Prescribed Fire Effects in Subalpine Spruce-Fir Slash. Northern Forest Research Centre Information Report NOR-X-3. 30 pp.

________. 1975. "Fire Behavior and the Use of Fire Retardants in Canadian Forests." Proc. 1975 Inter. Symp. Flam. and Fire Retard. pp. 175-86.

Kilgore, B.M. 1975a. "Integrated Fire Management on National Parks." Proc. Soc. Amer. For. Nat. Conv. 1975. pp. 178-88.

________. 1975b. "Restoring Fire to National Parks." Amer. Forests 81(3): 16-19, 57-59.

________. 1976. "From Fire Control to Fire Management: An Ecological Basis for Policies." Transactions of the 41st North American Wildlife and Natural Resources Conference. Wildlife Management Institute. pp. 477-93.

Kilian, Leonard A. 1971. "Public Information and Legal Aspects of Prescribed Burning." In Prescribed Burning Symposium Proceedings. April 14-16, 1971, Charleston, S.C. USDA Forest Service. pp. 130-38.

Kimmins, J.P. and M.C. Feller. 1976. "Effect of Clearcutting and Broadcast Slash Burning on Nutrient Budgets, Stream Water Chemistry and Productivity in Western Canada." Proc. of 16th Inter. Union of Forest Res. Organiz., Volume 1, Oslo, Norway. pp. 186-99.

Kinerson, R.S. and L.J. Fritschen. 1971. "Modeling a Coniferous Forest Canopy." Agr. Meteorol. 8:439-45.

________. 1973. "Modeling Air Flow Through Vegetation." Agr. Meteorol. 12:95-104.

Kisser, J. 1966. "Smoke Damages of Forest from the Biologic Standpoint." Presented at the Symposium on Smoke Damage to Forests in Austria, Vienna, Austria, November 9-11, 1965. pp. 7-48.

Kleinfield, N.R. 1972. Wall Street J. October 20. p. 1.

Klemmedson, J.O. 1976. "Effect of Thinning and Slash Burning on N and C in Ecosystems of young, Dense Ponderosa Pine." Forest Science 22(1): 45-53.

Knapp, H.J. 1977. "Potential of Industrial Wood Residue for Energy." Proceedings of Energy and the Wood Prod. Ind. FPRS #P-76-14. pp. 105-07.

Kohn, R.E. 1977. "A Benefit-Cost Analysis to Determine a Population Cut-off for a Statewide Ban on Leaf Burning." J. of Air Pollution Control Association 27(9):887-88.

Komarek, E.V. 1970. "Controlled Burning and Air Pollution: An Ecological Review." Annual Proc. Tall Timnbers Fire Ecol. Conf. 10:141-73.

_________. 1973. "Comments on the History of Controlled Burning in the Southern U.S." Proc. 17th Annual Arizona Watershed Symposium.

_________. 1974. "Further Remarks on Controlled Burning and Air Pollution." Annual Proc. Tall Timbers Fire Ecol. Conf. 13:279-82.

Komarek, E.V., B.B. Komarek and T.C. Carlysle. 1973. The Ecology of Smoke Particulates and Charcoal Residues from Forest and Grassland Fires. Misc. Publ. of Tall Timbers Research Station #3. 75 pp.

Kovalchik, B. and G. Blake. 1972. The Effect of Piling and Burning Versus Chopping of Logging Residues on Natural Regeneration of Serotinous Lodgepole Pine Forests. Missoula, Montana, Forest and Conservation Experiment Station Research Note 11. 4 pp.

Krauss, Paul E. 1976. "Adaptation of Meteorological Products for Specific Forestry Uses." In Proceedings of the Fourth National Conference on Fire and Forest Meteorology. St. Louis, Missouri, November 16-18, 1976. USDA Forest Service General Technical Report RM-32. pp. 27-30.

Lagerquist, Marianne. 1975. "New Particleboard Extruder Stretches Wood Residue Profits." Wood Prod. 80(4):53-54.

Lamb, Robert C. 1969. Nights Available for Prescribed Burns in the Lower Georgia Piedmont. USDA Forest Service Resarch Note SE-121.

__________. 1976. "Meteorological Resources for Land Management." In Proceedings of the Fourth National Conference on Fire and Forest Meteorology. St. Louis, Missouri, November 16-18, 1976. USDA Forest Service General Technical Report RM-32. pp. 44-47.

__________. 1977. "A Systematic Approach to Prescribed Burning Utilizing Weather." Unpublished draft outline.

Larson, R.W. and M.H. Goforth. 1970. TRANS - A Computer Program for the Projection of Timber Volume. USDA Agriculture Handbook #377. 24 pp.

__________. 1974. TRANS - A Timber Volume Projection Model. USDA Technical Bulletin #1508. 15 pp.

Larson, William H. "Fire Hazard Versus Air Pollution in the State of Washington." Proceedings of the Annual Meeting of the Society of American Foresters.

Lavdas, Leonidas G. 1978. Plume Rise from Prescribed Fires. Fifth Conference on Fire and Forest Meteorology, March 1978, Atlantic City, New Jersey.

__________. 1976. "A Groundhog's Approach to Estimating Insolation." Air Pollution Control Association J. 26(8):1.

Lawson, B.D. 1973. Fire Behavior in Lodgepole Pine Stands Related to the Canadian Fire Weather Index. Pac. For. Res. Cen., Canada Information Report #BC-X-76. 26 pp.

Lehmann, W.F. and R.L. Geimer. 1974. "Properties of Structural Particleboards from Douglas-Fir Forest Residues." For. Prod. J. 24(10):17-25.

Leisz, D. 1972. Where Residue Standards Cannot Be Met. Close Timber Utilization Committee Report. USDA Forest Service. pp. 13-21.

Lenic, J. 1972. "Joint Efforts of Scandinavian Countries Towards a Better Utilization of Residues in Forest Production." Les (Ljubljana) 24(7):152-53.

Leonard, G. 1972. Removal and Treatment of Residues. Close Timber Utilization Committee Report. USDA Forest Service. pp. 38-42.

Levno, Al. 1969. Increases in Maximum Stream Temperatures After Slash Burning in a Small Experimental Watershed. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Research Note PNW-110. 7 pp.

Lewis, W.M. Jr. 1975. "Effects of Forest Fires on Atmospheric Loads of Soluble Nutrients." Proc. of Symp. in Mineral Cycling in Southeastern Ecosystems. pp. 833-46.

Liseev, A.S. 1975. "Prohibit Fire as a Means of Clearing Felled Areas." Lesnaya Promyshlennost. 11:22.

Liu, M.L. et al. Assessment of the Feasibility of Modeling Wind Fields Relevant to the Spread of Bush Fires. Science Applications Inc.

Lowery, D.P., W.A. Hillstrom and E.E. Elert. 1977. Chipping and Pulping Dead Trees of Four Rocky Mountain Timber Species. USDA Forest Service Research Paper INT-193.

Lowry, W.P. 1967. "A Tentative Model to Establish Requirements for Use of Large Smoke Plumes from Prescribed Burning." Air Pollution Control Association PNW 5th Annual Meeting Proceedings. 12 pp.

Lyamin, V.A. 1971. The Yield of Products from Gasification of Coniferous Species Bark. National Science Foundation, Washington, D.C., Special Foreign Currency Science Information Program.

Lyon, L.J. 1971. Vegetal Development Following Prescribed Burning of Douglas-Fir in South-Central Idaho. USDA Forest Service Research Paper INT-105. 30 pp.

MacLean, C.D. 1976. *Timber Resources of Douglas County, Oregon.* USDA Forest Service Resource Bulletin PNW-66.

Maloney, T.M. 1973. "Bark Boards From Four West Coast Softwood Species." *Forest Prod. J.* 23(8):30-38.

Maloney, T.M., J.W. Talbott, M.D. Strickler and M.T. Lentz. 1976. "Composition Board from Standing Dead White Pine and Dead Lodgepole Pine." *Proceedings of the 10th Washington State University Symposium on Particleboard.* March 1976. Pullman, Washington. pp. 27-104.

Malte, P.C. 1975. *Pollutant Production From Forest Slash Burns.* Washington State University. Pullman College of Engineering Research Report 339. 34 pp.

Mann, M.J., C.A. Depew and R.C. Corlett. 1972. *A Laboratory Simulation of Wood Pyrolysis Under Field Conditions.* Presented at Combustion Institute, Western States Section, Spring Meeting, Seattle, Washington, April 24-25, 1972. Paper WSCI 72-13. 10 pp.

Martin, Robert E. and Arthur P. Brackebusch. 1974. "Fire Hazard and Conflagration Prevention." In *Environmental Effects of Forest Residues Management in the Pacific Northwest, a State-of-Knowledge Compendium.* USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-24. Portland, Oregon.

Martin, R.E., J.D. Dell and L.P. Nuenschwander. 1977. "Planning for Prescribed Burning in the Inland Northwest." *Presented at the Region 6 Eastside Prescribed Fire Workshop.* USDA Forest Service. 47 pp.

Martin, R.E., D.D. Robinson and W.H. Schaeffer. 1974. "Fire in the Pacific Northwest - Perspectives and Problems." *Proceedings Tall Timbers Fire Ecology Conf.* Tall Timbers Research Station. October 16-17, 1974, Portland, Oregon.

Martin, R.E. et al. 1976. *Task Force on Prescribed Burning.* Draft Final Report. Society of American Foresters.

Martin, R.E., R.W. Cooper et al. 1977. "Report of Task Force on Prescribed Burning." *J. For.* 75(5):297-301.

Mason, R.L. 1975. "Value of Residues for Fuel Versus Value for Products." *Proc. Wood Residue As an Energy Source.* FPRS #P-75-13. pp. 27-29.

Mathews, R.P. 1973. "The Smoky Question." *Pacific Search* 8(3):10-11.

________. 1976. *Use of Prescribed Burning to Enhance Regional Air Quality.* Preprint. Air Pollution Control Association.

Maxwell, W.G. and F.R. Ward. 1976a. *Photo Series for Quantifying Forest Residues in the: Coastal Douglas-Fir Hemlock Type, Coastal Douglas-Fir Hardwood Type*. USDA Forest Service General Technical Report PNW-51.

________. 1976b. *Photo Series for Quantifying Forest Residues in the: Ponderosa Pine Type, Ponderosa Pine and Associated Species Type, Lodgepole Pine Type*. USDA Forest Service General Technical Report PNW-52.

McCleese, W.L., F.L. Fenstermaker and R.F. Weinmann. 1976a. *A Management Contract to Improve Timber Sale Slash Treatment - Northern Region*. USDA Forest Service. June 1976.

________. 1976b. *A Management Contract to Improve Sale Slash Treatment - California Region*. USDA Forest Service. June 1976.

McCleese, W.L. et al. 1976c. *A Management Contract to Improve Timber Sale Slash Treatment, Brush Disposal Activity Review Action Plan and Report, Pacific Northwest Region*. USDA Forest Service. 65 pp.

McCleese, W.L., R.W. Fenchter, W.A. Hough et al. 1976d. *An Analysis of the Clean Air Act and Related Federal Regulations*. USDA Forest Service. Washington, D.C.

McComb, F. 1977. *ITF-FSU*. November 17, 1977. Exhibit B.

McCutchan, M.H. 1975. "Forest Fire Meteorology Research Network." *Automated Meteorological Systems*, pp. 351-59.

McHugh, W.M. 1977. *Energy Demend Modeling and Forecasting*. Northwest Energy Policy Project. Study Module II.

McKee, Herbert C. and Franklin W. Church. 1969. "Particulate Standards Keyed to Visibility and Citizen Complaints are Interim Measure. In A Symposium - The Technical Significance of Air Quality Standards." *Environmental Science and Technology* 3(6):542-48.

McLean, H.R. and F.R. Ward. 1976a. "Is 'Smoke-Free' Burning Possible?" *Fire Management* 37(1):10-13.

________. 1976b. "Air Curtain Combustion Device Evaluated for Burning Heavy Fuels." *R-6 Fuel Management Notes* 4(1):1-7.

McMahon, C.K. and P.W. Ryan. 1976. "Some Chemical and Physical Characteristics of Emissions from Forest Fires." *69th Annual Meeting of the Air Polution Control Association*. Portland, Oregon.

McMahon, C.K. and S.N. Tsoukalas. 1977. "Polynuclear Aromatic Hydrocarbons in Forest Fire Smoke." Proceedings of the Second International Symposium on Polynuclear Aromatic Hydrocarbons. September 28-30, 1977.

________. 1978. Polynuclear Aromatic Hydrocarbons in Forest Fire, Smoke, Carcinogenesis, Volume 3: Polynuclear Aromatic Hydrocarbons (P.W. Jones and R.I. Freudenthal, eds.). Raven Press, New York. pp. 61-73. (In press.)

McMullen, Robert N. 1971. "Land Clearing and Right-of-Way Disposal Problems." J. Environ. Health 34(2):211-12.

McNab, W.H. 1976. Prescribed Burning and Direct Seeding Old Clearcuts in the Piedmont (Pines Taeda, Logging Slash, Georgia). USDA Forest Service. Southeastern Forest Experiment Station Research Note SE-229. 4 pp.

Mersereau, R.C. and C.T. Dyrness. 1972. "Accelerated Mass Wasting After Logging and Slash Burning in Western Oregon." J. Soil Water Conserv. 27(3):112-14.

Meskimen, George. 1971 "Managing Forest Landscapes: Is Prescribed Burning in the Picture?" In Prescribed Burning Symp. Proceedings. April 14-16, 1971, Charleston, South Carolina. pp. 54-58.

Metcalf, M.E. 1965. Hardwood Timber Resources of the Douglas-fir Subregion. USDA Forest Service Resource Bulletin PNW-11.

Metz, Louis J. and Maurice H. Farrier. 1971. "Prescribed Burning and Soil Mesofauna on the Santee Experimental Forest." In Prescribed Burning Symposium Proceedings. April 14-16, 1971. Charleston, S.C. pp. 100-106.

Meyer, V.W. 1975. A Program for Improving Volume and Value Recovery in Logging Operations. Interim Task Force on Forest Slash Utilization. Exhibit E.

Miller, M.M. and J.W. Miller. 1974. "Succession After Wilfire in the North Cascades North Park Complex." Proceedings Tall Timbers Fire Ecology Conf. October 16-17, 1974. Tall Timbers Research Station, Portland, Oregon.

Miller, R.H.P. 1951. Gasogens. USDA Forest Service Forest Products Laboratory Report Number R1463.

Miller, Sharon R. 1976. "Industry Programs for Smoke Control in Forest Management Burning." In Air Quality and Smoke from Urban and Forest Fires Inter. Symp. National Academy of Sciences. pp. 352.

Mobley, Hugh E. 1974a. "Fire, Its Impact on the Environment." J. For. 72(7):414-17.

_________. 1974b. Air Pollution Regulations and Their Effect on Forest Management. Air Pollution Control Assoc., Pittsburgh, Pa., Southern Section and Technical Council, Control Technol., Agric. Air Pollut., Memphis, Tenn. pp. 29-38.

_________. 1976. Southern Forestry Smoke Management Guidebook. USDA Forest Service General Technical Report SE-10. pp. 140.

Mobley, Hugh E., E.V. Brender and D.T. Williams. 1975. "Preview of Smoke Management Guidelines." Forest Farmer Manual Edition. pp. 90-92.

Mobley, Hugh E., R.S. Jackson, W.E. Balmer et al. 1973. A Guide for Prescribed Fire in Southern Forests. USDA Forest Service.

Mohler, J.P. and R.E. Golson. 1975. Hydro-Ax and Nicolas Hydro-Mulcher Test Report. Washington Dept. of Natural Resources. DNR Note 10. 12 pp.

_________. 1976. TRAKMAC Evaluation. Washington Dept. of Natural Resources. DNR Note 13.

Moore, William R. 1974. "From Fire Control to Fire Management." Western Wildlands 1(3):11-33.

_________. 1976. "Fire!" National Wildlife 14(5):4-9.

Morgester, J.J. 1976. "The California Air Resources Board Program to Regulate Agricultural (Range and Forest) Burning." In Air Quality and Smoke from Urban and Forest Fires Inter. Symp. National Academy of Sciences. pp. 365-81.

Morris, William G. 1934. "Forest Fires in Western Oregon and Western Washington." Oregon Hist. Q. 35(4):313-39.

_________. 1966. "Guidelines Offered for Slash Burning." For. Ind. 93(10):62-63.

_________. 1970. "Effects of Slash Burning in Overmature Stands of the Douglas-Fir Region." Forest Sci. 16(3):258-70.

Mote, D. 1978. "International Paper Company - Acres of Slash Burned and Associated Costs." Private communication.

Mozolevskaia, E.G. and T.V. Galas'eva. 1975. "Trunk Pests in Slash Fires." Zashch. Rast. 3:48-49.

Munnich, K. 1978. "Scott Paper Company - Acres of Slash Burning, 1963-1977." Private communication.

Murad, J.L. 1972. "Effects of Prescribed Burning on Population Dynamics of Pine Forest Soil Nematodes." *11th Inter. Symp. on Nematology*.

Muraro, S.J. 1970a. "Slash Fuel Inventories from 70 mm Low-Level Photography." *Publ. For. Ser. Can.* #1268. p. 12.

———. 1970b. "Solid Fuel Aid to Slash Burning." *Truck Logger, Vancouver* 26(4):36.

———. 1971. "Prescribed Fire Impact in Cedar-Hemlock Logging Slash." *Publ. For. Ser. Can.* #1295. p. 20.

Murphy, C.E., Jr. et al. 1976. "Smoke Dispersal from a Controlled Fire Over a Logged Pine Forest Area." In *Proceedings of the Fourth National Conference on Fire and Forest Meteorology. November 16-18, 1976. St. Louis, Missouri.* pp. 228-31.

Murphy, James L. and Leo J. Fritschen. 1970. "Slash Burning: Pollution Can Be Reduced." *Fire Control Notes* 31(3):3-5.

Murphy, J.L. and C.W. Philpot. 1965. *Do Petroleum-Based Protective Coatings Add Fuel Value to Slash? USDA Forest Service Research* Note *PSW-81*. 3pp.

Murphy, James L., Leo J. Fritchen and Owen P. Carmer. 1970. "Research Looks at Air Quality and Forest Burning." *J. For.* 68(9):530:35. PSW-81. 3pp.

Mutch, Robert W. 1970. "Wildland Fires and Ecosystems - A Hypothesis." *Ecology* 51(6):1046-51.

———. 1974. "I Thought Forest Fires Were Black!" *Western Wildlands. p. 7.*

———. 1975. "Fire Management and Land Use Planning Today: Tradition and Changes in the Forest Service." *Western Wildlands*. pp. 13-19.

Mutch, Robert W. and George S. Briggs. 1976. "The Maintenance of Natural Ecosystems: Smoke as a Factor." In *Air Quality and Smoke from Urban and Forest Fire Inter. Symp.* *National Academy of Sciences. p. 255.*

Nappo, C.J. 1975. Time Dependent Mesoscale Wind Fields over Complex Terrain. Air Resources - Atmospheric Turbulence and Diffusion Laboratory, NOAA, Oak Ridge, Tennessee. ATDL Contrib. #75/6.

National Academy of Sciences. 1972. Particulate Polycyclic Organic Matter. Contract No. CPA 70-42. U.S. Environmental Protection Agency.

________. 1975. Directory of Fire Research in the United States, 1971-1973. Committee on Fire Research, Division of Engineering, National Research Council. 361 pp.

________. 1976. Air Quality and Smoke from Urban and Forest Fires Inter. Symp. October 24-26, 1973, Washington, D.C.

National Air Pollution Control Administration. 1969a. Air Quality Criteria for Particulate Matter. U.S. Public Health Service Report AP-49.

________. 1969b. Control Techniques for Particulate Air Pollutants. U.S. Public Health Service Report AP-51. p. 556.

________. 1970. Air Quality Criteria for Hydrocarbons. U.S. Public Health Service Report AP-64.

National Environmental Research Center. 1975. Scientific and Technical Assessment Report on Particulate Polycyclic Organic Matter (PPOM). Contract No. EPA-60016-74-001. U.S. Environmental Protection Agency.

National Forest Products Association. 1974. Summary of Research Projects: Fire in Forest Management. Smithsonian Science Information Exchange. 13 pp.

NcNitt, B. 1977. Modern Forest Management. ITF-FSU. Exhibit B.

Nelson, T. 1972. Conference Purpose and Expected Results. Close Timber Utilization Committee Report. USDA Forest Service. pp. 1-3.

Newport, Carl A. 1963. Forest Statistics for Chelan and Douglas Counties. USDA Forest Service Resource Bulletin PNW-5.

________. 1964. Forest Statistics for Northwest Oregon. USDA Forest Service Resource Bulletin PNW-7.

________. 1965. Timber Resource Statistics for the Pacific Northwest. USDA Forest Service Resource Bulletin PNW-9.

Newton, Michael. 1975. "Constructive Use of Herbicides in Forest Resource Management." J. Forestry 73(6):329.

________. 1977. Silvicultural Chemicals and Protection of Water Quality. EPA Report Number EPA 910/9-77-036.

Newton, M. 1977. " Herbicides in Forestry." Oregon Weed Control Handbook. pp. 116-21.

Nikleva, S. 1972. "The Air Pollution Potential of Slash Burning in Southwestern B.C." Forestry Chronicle 48(4):187-89.

Noll, K.E., P.K. Mueller and M. Imada. 1968. "Visibility and Aerosol Concentration in Urban Air." Atmos. Env. 2:465-75.

Norum, R.A. 1974. Smoke Column Height Related to Fire Intensity. USDA Forest Service Research Paper INT-157. 7 pp.

__________. 1975. "Characteristics and Effects of Understory Fires in Western Larch/Douglas-Fir Stands." Dissertation Abstracts Inter. B(1975) 36(5):1989.

__________. 1977. Preliminary Guidelines for Prescribed Burning Under Standing Timber in Western Larch/Douglas-Fir Forests. USDA Forest Service Research Note INT-229.

Norum, Rodney A., Nellie Stark and Robert W. Steele. 1974. "New Fire Research Frontiers in Montana Forests." Western Wildlands 1(3): 34-38.

Notzon, E.M. 1977. Nonpoint Source Control Guidance, Silviculture. U.S. Environmental Protection Agency, Office of Water Planning Standards. Technical Guidance Memorandum: Tech 37.

Oberle, M. 1969. "Forest Fires: Suppression Policy Has Its Ecological Drawbacks." *Science* 165(3893):568-71.

Oregon, State of. 1972. *Smoke Management Plan*. Directive 1-1-3-410.

________. 1976a. *Annual Report 1975 - Oregon Smoke Management Plan*. Department of Forestry. p. 36.

________. 1976b. *Memorandum: Slash Burning Averages, Update of 1968 Trends - Western Oregon*. Plans, Studies and Development Section, Forest Protection Division, Forestry Department.

________. 1977a. *Summary Report - Fall and Buck Study #53*. Interim Task Force on Forest Slash Utilization. Forest Management Subcommittee. Exhibit D.

________. 1977b. *Financing of the Oregon Forestry Department Fire Protection Program*. Interim Task Force on Forest Slash Utilization. Forest Management Subcommittee. Exhibit A.

________. 1977c. *Minutes of the Alternative Uses Subcommittee*. October 25, 1977. ITF-FSU.

________. 1977d. *Minutes of the Interim Task Force on Forest Slash Utilization*. Forest Management Subcommittee. October 12, 1977. Hearing Room F, State Capitol.

________. 1977e. *Forestry Program for Oregon, Timber Supply Today and Tomorrow*. Department of Forestry.

________. 1977f. *Minutes of the Interim Task Force on Forest Slash Utilization*. Forest Management Subcommittee. September 13, 1977. Hearing Room A, State Capitol.

________. 1977g. *Minutes of the Interim Task Force on Forest Slash Utilization*. Forest Management Subcommittee. September 27, 1977. Hearing Room A, State Capotol.

________. 1977h. *The Role of Fire in Oregon Forests*. General File 1-1-3-400, Smoke Management.

________. 1977i. *Changes in Smoke Management Operation Details*. Office of the State Forester, Forest Protection Division.

________. 1977j. *A Slash Burning Priority Rating Form for the Coastal Range - Western Oregon*. Department of Forestry.

________. 1977k. *Minutes of the Interim Task Force Slash Utilization*. Smoke Management Subcommittee.

Oregon, State of. 1977l. Minutes of the Interim Task Force on Forest Slash Utilization. Alternative Uses Subcommittee. October 13, 1977. Hearing Room A, State Capitol.

________. 1977m. Annual Report 1976 - Oregon Smoke Management Plan. Department of Forestry. p. 39.

________. 1977n. Miscellaneous Timber and Slash Statistics. ITF-FSU. September 27, 1977. Exhibit A.

________. 1977o. Wood Residue Utilization Methods. Hearing Minutes of Task Force on Forest Slash Utilization, Subcommittee on Alternate Use. October 4, 1977.

________. 1977p. Slash Burning in Western Oregon - 1976 Emissions by County. Department of Environmental Quality.

________. 1977q. Forest Land Burning Priority Rating System - Interim Policy. Forestry Department Memo dated July 15, 1977.

________. 1977r. ITF-FSU. Forest Management Subcommittee. November 17, 1977. Exhibit A.

________. 1977s. ITF-FSU. Forest Management Subcommittee Minutes. November 17, 1977. State Capitol.

________. 1977t. ITF-FSU. Alternative Uses Subcommittee Minutes. November 7, 1977. Portland State University.

________. 1977u. ITF-FSU. Alternate Uses Subcommittee. November 17, 1977. Exhibit A.

________. 1977v. ITF-FSU. Legislative Bill. November 7, 1977. Exhibit F.

________. 1977w. ITF-FSU. Smoke Management Subcommittee Minutes. November 10, 1977. University of Oregon, Eugene.

________. 1977x. ITF-FSU. Alternate Uses Subcommittee Minutes. November 17, 1977.

________. 1977y. ITF-FSU. Smoke Management Subcommittee. November 17, 1977. Exhibit C.

________. 1977z. ITF-FSU. Forest Management Subcommittee. November 17, 1977. Exhibit D.

Oregon, State of. 1977aa. ITF-FSU. Alternate Uses Subcommittee. November 17, 1977. Exhibit B.

__________. 1977bb. ITF-FSU. Minutes. November 17, 1977. Hearing Room A. State Capitol.

__________. 1977cc. ITF-FSU. Smoke Management Subcommittee Minutes. November 17, 1977. Hearing Room A. State Capitol.

__________. 1977dd. ITF-FSU. Smoke Management Subcommittee. November 17, 1977. Exhibit A.

__________. 1977ee. Report on the Joint Interim Task Force on Forest Slash Utilization. Senator John Powell, Chairman.

__________. 1977ff. FY '78 Federal Air Progam Grant Application. Department of Environmental Quality.

Oregon State University. 1968. "Slash Disposal Burning Sees Significant Reduction." For. Log 38(48):1,4.

__________. 1976. Forest Research Laboratory: Annual Report 1976.

__________. 1977a. Potential Energy Uses for Diseased and Beetle-Killed Timber and Forest Residues in the Blue Mountain Area of Oregon. USDE Research Project Proposal.

__________. 1977b. Densified Wood and Bark Fuels. Department of Forest Products. ITF-FSU. Exhibit B.

Osterli, Victor P. 1970. "Air Pollution Caused by Agriculture, Forestry and the Forest Products Industries: Combustion." Project Clean Air. California University, Berkeley, Task Force 5, Vol. 1, Section 5.

Ottawa, S.J. 1971. Prescribed Fire Impact in Cedar-Hemlock Logging Slash. Canadian Forestry Service Publication No. 1295. 20 pp.

Pacific Northwest Forest and Range Experiment Station. 1970a. *Annotated List of Publications of Pacific Northwest Forest and Range Experiment Station for Year 1969*. Portland, Oregon. 14 pp.

________. 1970b. *Annotated List of Publications of the Pacific Northwest Forest and Range Experiment Station for Year 1970*. Portland, Oregon. 18 pp.

Packham, D.R. and G.B. Peet. 1967. *Developments in Controlled Burning from Aircraft*. Commonwealth Scientific and Indust. Res. Organ., Melbourne. p. 18.

Pagni, P.J. and L.D. Houck. 1972. *Prescribed Burning*. Mich. Eng. Dept., U. Calif. TS-71-5.

Palmer, T.Y. and D.J. Anvil. 1975. *Recording Wind Velocity, Direction and Temperature in Fires by Logarithmic Technique*. USDA Forest Service Research Note PSW-304. 5 pp.

Pandolfo, J.P. et al. *Refinement and Validation of an Urban Meteorological - Pollutant Model*. USEPA Publ. #EPA-600/4-76-037. 22 pp.

Patterson, H.M. 1976. "Laws, Standards and Regulations for Smoke Abatement in Oregon." In *Air Quality and Smoke from Urban and Forest Fires Inter. Symp*. National Academy of Sciences. p. 183.

Pearson, H.A. 1967. *Relationship Between Timber and Cattle Production on Ponderosa Pine Range*. USDA Forest Service. Ft. Collins, Colorado.

Perkins, Carroll J. 1971. "The Effects of Prescribed Burning on Outdoor Recreation." In *Prescribed Burning Symposium Proceedings*. April 14-16, 1971, Charleston, South Carolina. pp. 59-63.

Pharo, J.A. 1976. *Aid for Maintaining Air Quality During Prescribed Burns in the South*. USDA Forest Service. Southeastern Forest Experiment Station Research Paper SE-152. 11 pp.

Pharo, J.A. and C.A. Hauck. 1975. *Smoke Dispersion Model for Prescribed Burning*. USDA Forest Service Research Note SE-220.

Philpot, C.W., C.W. George, A.D. Blakely et al. 1972. *The Effect of Two Flame Retardants on Particulate and Residue Production*. USDA Forest Service Research Paper INT-117. p. 14.

Pickford, Stewart G. 1972a. " Some Interaction of Open Burning Regulations with Fire Control Plans and Forestry Operations." Unpublished transcript.

________. 1972b. "The Study of Air Pollution From Open Burning of Logging Wastes: A Critical Analysis of a Field Experiment Performed by the University of Washington and the U.S. Forest Service." Ph.D. Thesis. Washington University, Seattle, College of Forest Resources. 109 pp.

Pickford, Stewart G. 1972c. Some Interactions of Open Burning Regulations with Fire Control Plans and Forestry Operations. Preprint, Combustion Institute, Western States Section. 16 pp.

Pierovich, John M. 1977a. "Facing Up to Smoke Management." Southern Lumberman, February 1, 1977. pp. 8-9.

________. 1977b. Smoke Management Research and Development Program - Charter. USDA Forest Service SEF&RES.

Pierovich, John M. and R.C. Smith. 1973. Choosing Forest Residues, Management Alternatives. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-7. 11 pp.

Pierovich, John M., E.H. Clarke, S.G. Pickford and F.R. Ward. 1975. Forest Residues Management Guidelines for the Pacific Northwest. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-33. 280 pp.

Pirsko, A.R. and L.M. Sergius. 1965. Causes and Behavior of a Tornadic Fire-Whirlwind. USDA Forest Service Research Note PSW-61.

Place, T.A. and T.M. Maloney. 1975. "Thermal Properties of Dry Wood-Bark Multilayer Boards." For. Prod. J. 25(1):33-39.

Pokela, R.W. 1972. "Rolling Chopper Disposes of Pine Slash." Fire Control Notes 33(2):7-8.

Pollanschuetz, J. 1966. "Method for Smoke Damage Determination as it is Presently Applied by the Federal Forestry Research Institute." Mitt. Forst. Bundesvers. 73:81-89.

Pong, W.Y. and J.W. Henley. 1976. Characteristics of Residues in a Balloon Logged Area of Old-Growth Douglas Fir. USDA Forest Service Research Note PNW-272.

Posekany, D. 1977. A Study of Forest Utilization in Relation to Slash Residues and Economics. Forest Slash Utilitization. Forest Management Subcommittee. Exhibit F.

Powers, Quincy. 1977. Western Markets for Slash Material. Weyerhauser Co., Exhibit A, ITF-FSU.

Prakash, C.B. and F.E. Murray. 1972. "Air Emissions from the Combustion of Wood Waste." Combus. Sci. Technol. 6(1-2):81-88.

Radke, L.F., J.L. Stith, D.A. Hegg and P.V. Hobbs. 1978. "Airborne Studies of Particles and Gases from Forest Fires." J. Air Pollution Control Association 28(1): 30-34.

Raisch, R. 1972. Improve Timber Utilization on State and Private Forest Lands. USDA Forest Service. Close Timber Utilization Committee Report. pp. 79-84.

Ralston, Charles W. and G.E. Hatchell. 1971. "Effects of Prescribed Burning on Physical Properties of Soil." In Prescribed Burning Symposium Proceedings. April 14-16, 1971, Charleston, South Carolina. pp. 68-85.

Ramaker, T.J. and W.F. Lehmann. 1976. High-Performance Structural Flakeboards from Douglas-fir and Lodgepole Pine Forest Residues. USDA Forest Service Resource Paper FPL-286.

Reeves, Hershel C. 1973. "Fire in the Management of Vegetation." J. of Geography 72(2):31.

__________. 1975. "Communicating the Role of Fire in the Forest." Fire Management 36(1):12-14.

Reid, D.G. and R.G. Vines. 1972. A Radar Study of the Smoke Plume from a Forest Fire. Commonwealth Scientific and Industrial Research Organization, Division of Applied Chemistry. Technical Paper 2. Melbourne, Australia. 15 pp.

Reiquam, H. 1970. "An Atmospheric Transport and Accumulation Model for Airsheds." Atmos. Env. 4:233-47.

Resch, H. 1977. ITF-FSU. November 17, 1977. Exhibit C.

Richardson, B.Y. 1976. Equipment for Reduction and Conversion of Forest Residues. USDA Forest Service. San Dimas Equipment Development Center.

__________. 1977. Equipment Development for Timber and Fuels Management. USDA Forest Service, San Dimas Equipment Development Center.

Richardson, James H. 1976. "U.S. Department of the Interior Programs for Smoke Control." In Air Quality and Smoke from Urban and Forest Fires Inter. Symp. National Academy of Sciences. p. 338.

Roberts, C.A. 1975. "Initital Plant Succession After Brown and Burn Site Preparation on an Alder-Dominated Brush Field in the Oregon Coast Range." Unpublished thesis. Oregon State University.

Roberts, Charles F. 1976. "Meteorological Problems in Smoke Management." In Air Quality and Smoke from Urban and Forest Fires Inter. Symp. National Academy of Sciences. p. 214.

Robinson, D.D. 1974. Fire in the Pacific Zone Forests. National Forest Product Association. 30 pp.

Robinson, E. and R.C. Robbins. 1969. Sources, Abundance, and Fate of Gaseous Atmospheric Pollutants. Stanford Research Institute. 77 pp.

__________. 1971. Emissions, Concentrations, and the Fate of Particulate Atmospheric Pollutants. Stanford Research Institute. 108 pp.

Roe, Al, W.R. Beaufait et al. 1971. "Fire and Forestry in the Northern Rocky Mountains - A Task Force Report." J. For. 69(8):464-70.

Rombach, J.L. 1977. The Importance of Slash Burning for Oregon's Future Timber Supply. Weyerhaeuser Company.

Rosene, J. 1978. Air Pollution Index Values. Olympic Air Pollution Authority.

Rothacher, J. and W. Lopushinsky. 1974. Soil Stability and Water Yield and Quality. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-24.

Roussopoulos, Peter J. and Von J. Johnson. 1976. Help in Making Fuel Management Decisions. USDA Forest Service. North Central Forest Experiment Station Research Paper NC-112. 20 pp.

Rudermann, F.K. 1977. Production, Prices, Employment and Trade in NW Forest Industries. USDA Forest Service PNW F&RES.

Ruskin, R.E. 1971. "Consideration in the Measurement of Pollution Effects on the Number of Cloud Condensation Nuclei." J. Applied Meteorology 10:994-1001.

Ruth, Robert H. and A.S. Harris. 1975. Forest Residues in Hemlock-Spruce Forests of the Pacific Northwest and Alaska: A State-of-Knowledge Review with Recommendations for Residue Management USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-39. 52 pp.

Ryan, B.C. 1977. "A Mathematical Model for Diagnosis and Prediction of Surface Winds in Mountainous Terrain." J. App. Meteor. 16(6)571-84.

Ryan, P.W. 1974. "Quantity and Quality of Smoke Produced by Southern Fuels in Prescribed Burning Operations." In Proceedings of the National Conference on Fire and Forest Meteorology. American Meteorological Society and Society of American Foresters. Lake Tahoe, California.

Saeman, J.F. 1975. "Fitting Wood into an Energy and Materials Policy." In Proceedings of Rocky Mountains Forest Industry Conference. pp. 1-6.

Sackett, Stephen S. 1975. "Scheduled Prescribed Burning for Hazard Reduction in S.E." J. For. 73(3):143-47.

__________. 1976. "Prescribed Fire Technology for Minimizing Smoke Hazards." In Air Quality and Smoke from Urban and Forest Fires Inter. Symposium. National Academy of Sciences. pp. 241-46.

Sackett, Stephen S. and D.D. Wade. 1970. "Prescribed Burning at Night." For. Farmer 29(5):11.

Saint Louis City, Missouri. 1974. Waste Wood and Bulky Refuse Disposal, Saint Louis Facilities. Final Report. 50 pp.

Sandberg, David V. 1975. "Measurements of Particulate Emissions from Forest Residues in Open Burning Experiments." Ph.D. Thesis. College of Forest Resources, University of Washington.

__________. 1977. ITF-FSU. November 7, 1977. Exhibit A.

Sandberg, David V. and Robert E. Martin. 1975. Particle Sizes in Slash Fire Smoke. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Research Paper PNW-199. 7 pp.

Sandberg, D.V. and S.G. Pickford. 1974. "An Approach to Predicting Slash Fire Smoke." In Proceedings of Tall Timbers Fire Ecology Conference. October 16-17, 1974. Tall Timbers Research Station, Portland, Oregon.

Sandberg, D.V., S.G. Pickford and E.F. Darley. 1975. "Emissions from Slash Burning and the Influence of Flame Retardant Chemicals." J. Air Pollution Control Assoc. 25:278-81.

Sandberg, D.V. et al. 1978. Fire Effects on Air Quality: A State of the Knowledge Report. Review Draft. USDA Forest Service, No. FS-8520.

Sando, R.W. 1969. The Current Status of Prescribed Burning in the Lake States. USDA Forest Service Research Note NC-81. 2 pp.

Sandor, J. 1972. Forest Residues in the East. Close Timber Utilization Committee Report. USDA Forest Service. pp. 85-89.

Schaefer, Vincent J. 1969. "The Inadvertent Modification of the Atmosphere by Air Pollution." Bulletin on the American Meteorological Society 50:199-206.

__________. 1974. "Some Physical Relationships of Fine Particle Smoke." Ann. Proc. Tall Timbers Fire Ecol. Conf.

__________. 1976. "The Production of Optimum Particle Smokes in Forest Fires." In Air Quality and Smoke from Urban and Forest Fires Inter. Symp. National Academy of Sciences. p. 27.

Schuldt, J.P. and J.O. Howard. 1974. Oregon Forest Industries 1972 Wood Consumption and Mill Characteristics. Oregon State University Extension Service. p. 113.

Serrell, M.A. 1974. "Wood Waste: A Modern Fuel." ASME National Incinerator Conference Proc. Pap. Miami, Florida, pp. 267-70.

Shearer, R.C. 1975. Seedbed Characteristics in Western Larch Forests after Prescribed Burning. USDA Forest Service Research Paper INT 167. 26 pp.

Shendrikar, A.D. and P.W. West. 1973. "Determination of Selenium in the Smoke from Trash Burning." Envir. Letters 5(10):29-35.

Shenk, W.D. and R.H. Harlan. 1972. "Crusher-cutter Efficiency Disposes of Slash." Fire Control Notes 33(2):5-7.

Shum, Y.S. and W.D. Loveland. 1974. "Atmospheric Trace Element Concentrations Associated with Agricultural Field Burning in the Willamette Valley of Oregon." Atmos. Environ. 8:645-55.

Siegel, G.R. 1975. "Wood Residue as a Fuel in the Commercial Production of Electricity." Proc. Wood Residues as an Energy Source. FPRS #P-75-13. pp. 94-97.

Silversides, C.R. 1969. "Changing Harvesting Techniques and Equipment: How They Affect Forest Protection." Pulp Paper Mag. Can. 70(19):105-06.

Sims, H.P. 1974. "Some Ecololigical Effects of Prescribed Burning on Cut-Over Jack Pine Sites, S.E. Manitoba." Diss. Abstr. Int. B(1974) 34(9): 4147-48.

Skarra, P.E. 1969. "Some Observations on Indian Forests and Prescribed Burning." In Tall Timbers Fire Ecology Conference. pp. 209-12.

Slowik, A.A. and J.J. Austin. 1977. "Plume Dispersion Modeling in Complex Terrain Under Stable Atmospheric Conditions." In Proceedings of Air Pollution Control Association. June 20-24, 1977.

Smith, David H. 1962. The Practice of Silviculture. 7th edition. John Wiley & Sons, New York. p. 578.

Smith, J.H.G. 1970. "A British Columbian View of the Future of Prescribed Burning in Western North America." Commonw. For. Rev. 49(4)#142:356-67.

Smith, J.H. and D.E. Gilbert. 1974. "Rates of Spread and Fire Damage to Timber Cover Types in British Columbia." In Proceedings Tall Timbers Fire Ecology Conference. October 16-17, 1974. Tall Timbers Research Station. Portland, Oregon.

Smith, James R. and Jack C. Suggs. 1976a. "Goals of a National Program in Smoke Research." In Air Quality and Smoke from Urban and Forest Fires International Symposium. National Academy of Sciences. p. 296.

_________. 1976b. "Smoke Composition." In Air Quality and Smoke from Urban and Forest Fires Intern. Symp. National Academy of Sciences, p. 296.

Smith, R. 1977a. ITF-FSU. November 10, 1977. Exhibit D.

_________. 1977b. ITF-FSU. November 10, 1977. Exhibit K.

_________. 1977c. ITF-FSU. November 10, 1977. Exhibit L.

_________. 1977d. ITF-FSU. November 10, 1977. Exhibit M.

"Smoke from Prescribed Burning." Bush Fire Bull. 9(4):10-11, 1974.

Sneeawjagt, R.J. and W.H. Fandsen. 1977. "Behavior of Experimental Grassfires vs. Predictions Based on Rothermel's Fire Model." Can. J. of For. Res. 7(2):357-67.

Snowden, W.D. 1977. Alternative Fuel Evaluation - WA Corrections Center. Alsid, Snowden & Associates. State of Washington, Department of General Administration. Contract Number 76-79214.

Snowden, W.D. et al. 1975. Source Sampling Presidential Fireplaces for Emission Factor Development. U.S. Environmental Protection Agency Agency Publication Number 450/3-76-010.

Snyder, G.G. et al. 1975. Clearcutting and Burning Slash Alter Quality of Stream Water in Northern Idaho. USDA Forest Service. Intermountain Forest and Range Experiment Station Research Paper INT-168. 34 pp.

Society of American Foresters. 1977. "Prescribed Burning: A Position of the Society of American Foresters." J. For. 75(11):744-45.

Southwest Interagency Fire Council. 1970. Prescribed Burning and Management of Air Quality. Seminar Sponsored by Southwest Interagency Fire Council, Tuscon, Arizona, November 21, 1968. 81 pp.

Sprout, Waldron & Co. 1961. Bark Pelleting . . . A New Solution to an Old Problem.

Stankey, G.H. 1976. Wilderness Fire Policy: An Investigation of Visitor Knowledge and Beliefs. USDA Forest Service Research Paper INT-180.

Steele, Robert. 1974. "Smoke Considerations Asociated with Understory Burning in Larch/Douglas-Fir." Proc. Tall Timbers Fire Ecology Conf. pp. 597-607.

Steele, R.W. and W.R. Beaufait. 1969. *Spring and Autumn Broadcast Burning of Interior Douglas-Fir Slash*. Montana Forest Conserv. Exp. Sta. Bull. 36. 12 pp.

Steffensen, M. 1973. "Pellets from Sawmill Waste for Efficient Fuel." *Proc. Forest Prod. Res. Soc., California Section*. November 1-2, 1973.

Stern, F. 1977. *ITF-FSU*. November 10, 1977. Exhibit I.

Stewart, R.E. 1976. "Chemical Site Preparation in the Inland Empire." *Proc. of Washington State University Conference*. February 1976. pp. 158-71.

Stinson, M. 1977. *ITF-FSU*. November 10, 1977. Exhibit G.

Stockstad, D.S. 1975. *Spontaneous and Piloted Ignition of Pine Needles*. USDA Forest Service Research Paper INT-194. 14 pp.

Stoddard, L.A. 1931. *The Bob-White Quail, Its Habits, Preservation and Increase*. Scribner, New York.

Stoddard, L.A., A.D. Smith and T.W. Box. 1975. *Range Management*. 3rd edition. McGraw-Hill, New York. pp. 435-38.

Stone, Earl L., Jr. 1971. "Effects of Prescribed Burning on Long-Term Productivity of Coastal Plain Soils." In *Prescribed Burning Symposium Proceedings*. April 14-16, 1971. Charleston, S.C. pp. 115-29.

Stone, R.N. 1976. "Timber, Wood Residues, and Wood Pulp on Sources of Culture." In *Biotechnical and Bioengineering Symposium Number 6*. pp. 223-34.

Stone, R.N. and J.F. Saeman. 1977. "World Demand and Supply of Timber to the Year 2000." *For. Prod. J.* 27(10):49-54.

Sturos, John A. 1973. *Segregation of Foliage from Chipped Tree Tops and Limbs*. North Central Forest Experiment Station Research Note NC-146. 5 pp.

Sutherland, C.F. Jr. 1973. "Cost of Forest Closure in Two Oregon Counties." *J. For.* 71(10):644-47.

Swanson, J.R. 1974. "Hazard Abatement by Prescribed Underburning in West Side Douglas-fir." In *Proc. Tall Timbers Fire Ecology Conference*. October 16-17, 1974. Tall Timbers Research Station. Portland, Oregon.

Swanson, F.J., G.W. Lienkaemper and J.R. Sedell. 1976. History, Physical Effects, and Management Implications of Large Organic Debris in Western Oregon Streams. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report 56. 15 pp.

Swanston, D.N. 1974. Slope Stability Problems Associated with Timber Harvesting in Mountainous Regions of the Western U.S. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-21. 14 pp.

Sweet, H.R. and R.H. Fetrow. 1975. "Ground Water Pollution by Wood Waste Disposal." Ground Water 13(2):227-31.

Takeshita, Takenari, Toshio Yasutomi and Teiji Yokota. 1975. "Continuous Carbonization of Crushed Waste Wood in a Stirred Fluidized Bed." *Funtai Kogaku Kenkyu Kaishi* 12(4):199-203.

Tall Timbers Research Station. 1974. *Proceedings of the Tall Timbers Fire Ecology Conference*. October 16-17, 1974. Portland, Oregon.

Tang, W. 1970. *Study of Air Flow in and Above a Forest Over Different Terrain*. Defense Documentation Center.

Tangren, C.D. 1976a. "Smoke from Prescribed Fires." *Forest Farmer* 35(10):6-7.

Tangren, C.D., C.K. McMahon and P.W. Ryan. 1976. "Contents and Effects of Forest Fire Smoke." *Southern Forestry Smoke Management Guidebook*. USDA Forest Service General Technical Report SE-10.

Tarrant, Robert F. 1956a. "Effects of Slash Burning on Some Soils of the Douglas-fir Region." *Soil Science Society of America Proceedings* 20:408-11.

__________. 1956b. "Effects of Slash Burning on Some Physical Soil Properties." *Forest Science* 2:18-22.

Tatom, J.W., A.R. Colcord, J.A. Knight, L.W. Elston and P.H. Har-Oz. 1975. "Mobile Pyrolytic System - Agricultural and Forestry Wastes into Clean Fuels." In *Proc., Cornell Agric. Waste Manage. Conf.* Published by Ann Arbor Sci. Publ., Inc. Michigan. pp. 271-88.

Taylor, A.R. 1975. *Fire Ecology Questions Survey of Research Needs*. USDA Forest Service General Technical Report INT-18.

Thermal Efficiency, Inc. 1977. *Environmental Waste - Energy Conversion System*.

Thompson, Robert E. 1974. *Process for Recovering Forest Product Plant Wastes.* Environment Inc., Guilford, Connecticut. U.S. Pat. 3,783,128. 16 pp.

Thornton, P. 1972. *Research Implementation*. Close Timber Utilization Committee Report. USDA Forest Service. pp. 74-78.

Thuillier, Richard H. and James S. Sandberg. 1971. "Development of a Meteorologically Controlled Agricultural Burning Program." *Bull. Am. Meteorol. Soc*. 52(12):1193-1200.

Towne, R.S. 1975. "Woodwaste Handling Trends." *Proc. of Wood Residues as an Energy Source*. FPRS #P-785-13. pp. 42-45.

"Trench Burner Could Answer Slash Problems." *Bri. Col. Lumberman* 58(2): 32-33.

Truax, M.R. 1977. "Visibility Criteria for Class 1 Airsheds." Private Communication.

_________. 1978. "Simpson Timber Company Projected Acres and Costs for Slash Burning." Private Communication.

Truesdale, P.S. 1969. "Pollutants of the Prescribed Burning Program of the Bureau of Indian Affairs." In _Tall Timbers Fire Ecology Conference_. pp. 236-40.

University of California. 1971. *Prescribed Burning*. Berkeley College of Engineering, Thermal Systems Division, Natural Science Foundation Grant GY-9112. Report No. TS-71-5.

U.S. Department of Agriculture Forest Service. 1971. *Prescribed Burning Symposium Proceedings*. Southeast Forest Experiment Station. 160 pp.

________. 1972a. "Fuel Treatment Methods." *Forest Service Manual*, Title 5153.

________. 1972b. *Multipurpose Brushland Modification on Seven Plant Associations on National Forest Lands in California*. Region 5 Draft Environmental Impact Statement No. USDA-FS-DES(ADM)-72-33. San Francisco, California. 72 pp.

________. 1972c. "Fire in the Environment." *Symp. Proceed*. May 1-5, 1972. Denver, Colorado. 151 pp.

________. 1972d. *Assessment of Present Position, Needs and Conclusions, and Recommndations*. Close Timber Utilization Committee Report.

________. 1972e. *Forest Born of Fire*. Northern Region. Missoula, Montana. U.S. Government Printing Office. 1972-796-959.

________. 1973a. "Slash Treatment Statistics, PNW National Forest Lands, 1963-1972." Unpublished memorandum.

________. 1973b. *Slash Disposal Information Sheet*. Region 6.

________. 1973c. *Big Game Habitat Improvement. Burning of Seral Brushfields in the Spokane, St. Joe, Clearwater, and Salmon River Drainages of Idaho*. Northern Region Final Environmental Impact Statement No. USDA-FS-FES(ADM)-73-15. Missoula, Montana. 84 pp.

________. 1973d. *Northern Region's Slash Disposal Program*. Northern Region Draft Environmental Impact Statement USDA-FS-DEM(ADM)-73-79. Missoula, Montana. 126 pp.

________. 1973e. *Slash Disposal Information Sheet*. Oregon Interim Task Force.

________. 1974a. *Fire Management Considerations for Land Use Planning*. Washington, D.C.

________. 1974b. "New 'Hydro-Ax' Machine Tested for Precommercial Thinning and Slash Treatment." *R-6 Fuel Management Notes* 2(2):1-4.

________. 1974c. *Logging Leftovers: A Study of Wood Use*. Pacific Northwest Forest and Range Experiment Station.

U.S. Department of Agriculture Forest Service. 1975a. *Logging Leftovers: A Study of Wood Use*. PNW F&RES. 8 pp.

________. 1975b. "Timber Shaded Fuelbreaks in Region 6." *R-6 Fuel Management Notes* 3(1):1-13.

________. 1975c. "Projecting Costs for Use in B.D. Appraisals - An Example." *R-6 Fuel Management Notes* 3(3):1-3.

________. 1975d. *Fuel Management for the Central Rocky Mountains and the Southwest*. Research Work Unit.

________. 1975e. *1974 Wildfire Statistics*. Cooperative Fire Protection Staff Group, State and Private Forestry.

________. 1976a. *Forest Interpreter's Primer on Fire Management*. TT-53.

________. 1976b. *Research Publications List, 1922-1976*. General Technical Report RM-31.

________. 1976c. *Fire Management in the Selway-Bitteroot Wilderness - A Proposed Change*. Final Environmental Statement. U.S. Government Printing Office. 1976-796-018/10.

________. 1976d. 1975. *Renewable Resource Program, Oregon and Washington*. Pacific Northwest Summary.

________. 1976e. *The National Forest Management Act of 1976*. Current Information Report No. 16. 28 pp.

________. 1977a. "Rogue River National Forest Conducts Westside Prescribed Underburning Demonstration Trip." *R-6 Fuel Management Notes* 5(3):1.

________. 1977b. "Free-Use Firewood Permits - Utilizing Public Assistance in Fuels Management." *R-6 Fuel Management Notes* 5(1):1.

________. 1977c. "Forest Service Energy Research Coordination." Communication Memorandum.

________. 1977d. *Forest Survey Field Instructions for Eastern Oregon*. PNW F&RES. 67 pp.

________. 1977e. *Improved Harvesting Program: Field Instructions*. State and Private Industry. Interim Task Force on Forest Slash Utilization. Forest Management Subcommittee. October 12, 1977. Exhibit C.

________. 1977f. *National Fuel Inventory and Appraisal Research Project*. Washington, D.C.

U.S. Department of Agriculture Forest Service. 1977g. Vegetation Management with Herbicides. Draft Environmental Statement. Region 6.

_________. 1977h. The Nation's Renewable Resources - An Assessment, 1975. Forest Res. Report #21.

U.S. Department of Commerce. 1974. Clouds. National Oceanic and Atmospheric Administration. U.S. Gov't. Printing Office 1974-0-549-662.

U.S. Environmental Protection Agency. 1977a. Technical Support Document on the Phase Down of Oregon Open Field Burning. Region X. p. 16.

_________. 1977b. Technical Support Document on the Phase Down of Oregon Open-Field Burning. Region X. p. 88.

U.S. General Accounting Office. 1973. Increased Use of Felled Wood Would Help Meet Timber Demand and Reduce Environmental Damage in Federal Forests. Washington, D.C. 52 pp.

Urone, P., W.H. Benner, C.K. McMahon and P. Ryan. 1977. "Photochemical Potential of Forest Fire Smoke." In Proceedings of APCA. June 20-24, 1977.

Vandegrift, A.E. et al. 1971. *Particulate Pollutant System Study. Volume I: Mass Emissions.* PB-203-128. National Technical Information Service. U.S. Department of Commerce. Springfield, Virginia.

VanDerveer, Paul D. and Kenneth E. Lowe (eds.). 1975. "Fiber Conservation and Utilization." In *Proceedings of the May 1974 Pulp and Paper Seminar.* Chicago, Illinois. San Francisco, Miller Freeman Publications. 288 pp.

VanGelder, Randall J. 1976. "A Fire Potential Assessment Model for Brush and Grass Fuels." *Fire Management Notes* 37(3):14-16.

VanSickle, C. 1972. *Quality and Character of Logging Residues.* USDA Forest Service. Close Timber Utilization Committee Report. pp. 4-8d.

VanVliet, A.C. 1971. *Converting Bark into Opportunities.* School of Forestry. Oregon State University.

Veilleux, J.-M. 1972. *Effects of Controlled Burning on the Physical and Chemical Properties of the Humus Layer.* Ministry of Soils and Forests Research Note 9. Quebec. 30 pp.

Vines, R.G. 1974a. "Bush-Fire Smoke and Air Quality." *Proc. 13th Tall Timbers Fire Ecol. Conf.* pp. 303-307.

__________. 1974b. "Air Movements Above Large Bush-Fires." *Proc. 13th Tall Timber Fire Ecol. Conf.*

__________. 1975. "Bushfire Research in C SIRO." *Search* 6(3):73-8.

Vines, R.G., L. Gibson, A.B. Hatch, N.K. King and D.A. MacArthur. 1971. *On the Nature, Properties, and Behavior of Bush-Fire Smoke.* Commonwealth Scientific and Industrial Research Organization, Division of Applied Chemistry Technical Paper 1. Melbourne, Australia. 33 pp.

Viro, P.J. 1969. "Prescribed Burning in Forestry." *Commmun. Inst. For. Fenn.* 67(7):49.

Vlug, H. and J.H. Borden. 1973. "Soil Acari and Collembola Populations Affected by Logging and Slash Burning in a Coastal British Columbia Coniferous Forest." *Environ. Entomol.* 2(6):1016-23.

Vogl, Richard J. 1971. "The Future of Our Forests." *Ecology Today* 1(1):6.

__________. 1974. "Ecologically Sound Management: Modern Man's Road to Survival." *Western Wildlands* 1(3):6-10.

Vogl, Richard J. and C. Ryder. 1969. "Effects of Slash Burning on Conifer Reproduction in Montana's Mission Range." Northwest Sci. 43(3):135-47.

Vyse, A.H. and S.J. Muraro. 1973. Reduced Planning Cost, A Prescribed Fire Benefit. Canadian Forestry Service. Pacific Forest Research Centre Information Report BC-X-84. 13 pp.

Wade, D.D. 1969. "Research on Logging Slash Disposal by Fire." Proc. 9th Tall Timber Fire Ecol. Conf. pp. 229-34.

Wagar, J.A. 1974. Recreation and Esthetic Considerations. USDA Forest Service. Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-24.

Wagener, W.W. and H.R. Offord. 1972. Logging Slash: Its Breakdown and Decay at Two Forests in Northern California. USDA Forest Service Research Paper PSW-83. 11 pp.

Waggener, T.R. 1976. Equity and Redistribution Implications of Residues Policy, A Social View. PACFORNET WU-FOR-76-09-104.

Wagner, C.E. 1970. "Temperature Gradients in Duff and Soil During Prescribed Fires." Bi-Mon. Res. Notes 26(4):42.

Wahlgren, H.E., R. Barger and H. Marx. 1977. Stretching Our Nation's Timber Supply: Close Timber Utilization. USDA Forest Service Program Aid 1189.

Wake, B.F. et al. 1974. "Is Prescribed Burning Compatible with Environmental Quality - A Panel Discussion." Proc. of Tall Timbers Fire Ecology Conf. pp. 627-44.

Wall, B.R. 1972. Log Production in Washington and Oregon - An Historical Perspective. USDA Forest Service Resource Bulletin PNW-42.

Walsh, Stephen and Richard W. Boubel. 1975. Combustion of Wood Residue in Conical Burners, Emission Controls and Alternatives. EPA, Washington, D.C. EPA/340/1-76/002.

Ward, Darold E. 1974. Particulate Source Strength Determination for Low-Intensity Prescribed Fires. Southern Section and Technical Council, Control Technol. Agric. Air Pollut., Memphis, Tennessee. pp. 39-54.

Ward, D.E. and R.C. Lamb. 1971. "Prescribed Burning and Air Quality - Current Research in the South." Proc. 10th Tall Timbers Fire Ecol. Conf. pp.129-40.

Ward, Darold E. and Ernest R. Elliot. 1976. "Georgia Rural Air Quality: Effect of Agricultural and Forestry Burning." APCA J. 26(3):216.

Ward, Darold E., Charles K. McMahon and Ragnar W. Johansen. 1976. "An Update on Particulate Emissions from Forest Fires." 69th Air Pollution Contr/ Assoc. Ann. Meeting, Portland, Oregon. 15 pp.

Ward, D.E., C.K. McMahon and D.D. Wade. 1974. "Particulate Source Strength Determination for Low-Intensity Prescribed Fires." In Specialty Conference on Control Technology for Agricultural Air Pollutants. Air Pollution Control Association. Memphis, Tennessee.

Ward, F.R. 1975. *Evaluations on Accelerating Wood Decomposition in the Field.* USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Research Note PNW-245. 8 pp.

Ward, F.R. and H.R. McLean. 1976. *Burying Forest Residue - An Alternative Treatment.* USDA Forest Service. Pacific Northwest Forest and Range Experiment Station Resource Note PNW-270. Portland, Oregon. 7pp.

Ward, F.R. and J. W. Russel. 1975. *High-Lead Scarification: An Alternate for Site Preparation and Fire Hazard Reduction.* *Fire Management.* pp. 3,4,19.

Warner, J. 1968. "A Reduction in Rainfall Associated with Smoke from Sugar Cane Fires - An Inadvertent Weather Modification?" *J. Appl. Meteor.* 7:247-51.

Warren, W.G. and P.F. Olson. 1964. "A Line Interest Technique for Assessing Logging Waste." *For. Sci.* 10(3):267-76.

Washington State Department of Natural Resources. 1975a. *Smoke Management Program*, 1975.

__________. 1975b. "Prescribed Slash Burning: An Essential Tool in Forest Management." *Washington Dept. Nat. Res. Bulletin.*

__________. 1975c. *Washington Forest Productivity Study.* Project NR-1014.

__________. 1977. *1976 Annaul Fire Statistics.*

Wasserman, S.E. and J.D. Kanupp. 1968. *A Climatology of Weather That Affect Prescribed Burning Operations at Columbia, South Carolina. Scientific Services Div. and Weather Bureau Forecast Center, Columbia*, South Carolina. WB-TM-ER-EE. 33 pp.

"Waste Problems of Agriculture and Forestry." *Environ. Sci. and Tech.* 2:498, July 1968.

Wayne, L.G. and M.L. McQueary. 1975. *Calculation of Emission Factors for Agricultural Burning Activities. U.S. Environmental Protection Agency Publication Number 450/3-75-087.*

Weaver, H. 1964. "Fire and Management Problems in Ponderosa Pine." In *Proceedings of the 3rd Annual Tall Timbers Fire Ecology Conference. April 9-10, 1964.* pp. 61-79.

__________. 1967. "Fire and Its Relationship to Ponderosa Pine." In *Proceedings of the California Tall Timbers Fire Ecology Conference. November 9-10, 1967.* pp. 127-49.

Weaver, H. 1974. "Western United States." In T.T. Koslovski (ed.), *Effects of Fire on Temperate Forests*. New York, Academy Press.

Welk, J.B. 1977. *Horn Prescribed Burn*. Environmental Analysis Report. Okanogan National Forest. Tonasket Ranger District.

Wellman, E. 1976. *Emission Test Report - E.W. Hines Lumber Co. #5 Boiler*. BWR Associates, Environmental Consultants.

Wells, Carol G. 1971. "Effects of Prescribed Burning on Soil Chemical Properties and Nutrient Availablility." In *Prescribed Burning Symposium Proceedings*. April 14-16, 1971. Charleston, South Carolina. pp. 86-99.

Western Forestry Industrial Assoc. 1977. *ITF-FSU*. November 10, 1977. Exhibit N.

"What to do About Slash." *Truck Logger* 25(8):7-8. Vancouver, 1969.

Widden, P. 1975. "The Effects of a Forest Fire on Soil Microfungi." *Soil Biol. and Biochem*. 7(2):125-38.

Willamette National Forest. 1977. *Smoke Management*. Directive 1-1-3-410. February. 40 pp.

Williams, D.E. 1971. *Forest Fires and Pollution*. Convention September 26-30, Cleveland, Ohio.

Williams, Dansey T. 1972. "Smoke at Palm Beach During the 1971 Everglades Wildfires." *Manual of the Fire Danger and Fire Weather Seminar*. USDA Forest Service, Bureau of Land Management (U.S. Department of the Interior), and National Weather Service (National Oceanic and Atmospheric Administration). 9 pp.

__________. 1974. "A Smoke Volume Model for Prescribed Fire." In *Symposium on Atmospheric Diffusion and Air Pollution*. September 9-13, 1974. Santa Barbara, California. Published by the American Meteorological Society, Boston, Massachusetts. pp. 159-62.

Williams, E.B. 1975. *The Value of Fire in Management of the Forests of the Southern Region*. National Forest Products Association. 62 pp.

Wilson, C.A. 1977. *How to Protect Western Conifer Plantations Against Fires*. Presented: Western Forestry and Conservation Association, November 30, 1977.

Wilson, C.L. and J.D. Dell. 1971. "The Fuels Buildup in American Forests. A Plan of Action and Research." *J. For*. 69:471-75.

Wilson, K.O. 1970. "Forest Fuels Management - The Problem and the Challenge." *J. For*. 68(5):274-79.

Wilson, W.H. 1977. *WOODEX Pelletized Wood Fuel Test Report - Toppenish #2 Boiler*. Toppenish District U and I, Inc.

Winkworth, Ralph C. 1976. "State Forestry Programs for Smoke Control." *In Air Quality and Smoke from Urban and Forest Fires Inter. Symp*. National Academy of Sciences. p. 335.

Woodward, Paul M., Stewart G. Pickford and Robert E. Martin. 1976. "Predicting Weights of Douglas-fir Slash for Materials up to 3 Inches in Diameter." *Fire Management Notes* 37(3):8-9, 12.

Worthington, D. 1972. *Cleanup Standards for Residues on National Forests*. USDA Forest Service. Close Timber Utilization Committee Report. pp. 9-12.

Worthington, R.E. 1977. *Fire is an Important Management Tool . . . .* ITF-FSU. Exhibit E.

Yamate, George. 1973. Development of Emission Factors for Estimating Atmospheric Emissions from Forest Fires. IIT Research Institute Final Report. Chicago, Illinois. 147 pp.

________. 1974. Emissions Inventory from Forest Wildfires, Forest Managed Burns, and Agricultural Burns. USEPA Publ. #450/3-74-062.

Yamate, George, John Stockham, William Vatavak, and Charles Mann. 1975a. "An Inventory of Emissions from Forest Wildfires, Forest Managed Burns, and Agricultural Burns." Presented at 68th Ann. Meeting Air Pollut. Contr. Assoc. 12 pp.

Yamate, George, John Stockham, David Becker, Thomas Waterman, Patricia Llewellen, and William M. Vatavak. 1975b. "Development of Emission Factors for Estimating Atmospheric Emissions for Forest Fires." Presented at 68th Ann. Meeting Air Pollut. Contr. Assoc. 14 pp.

Young, Harold E. 1975. "Utilization of Forest Residues, A Segment of the Complete Tree Concept." Proc. Soc. of Amer. Foresters Nat. Conv. pp. 479-84.

Young, R. 1972. Residue Utilization Research at Forest Products Laboratory. Close Timber Utilization Committee Report. USDA Forest Service. pp. 45-49.

Yurich, S. and J. L. Volz. 1973. The Natural Role of Fire. USDA Forest Service and U.S. Department of the Interior, National Park Service. U.S. Government Printing Office.

Zerbe, J. 1972. Particleboard from Residues. Close Timber Utilization Committee Report. USDA Forest Service. pp. 50-54a.

APPENDIX D

Listing of Field Experts Contacted for This Report

Key:

1 - Fire and fuels management

2 - Forestry burning emissions and impacts on air quality

3 - Burning techniques

4 - Alternatives to burning

E - Economics

M - Management

R - Research

Adams, Thomas C.
Principal Economist, Forest Residue Program
USDA-FS PNWF & RES
809 NE 6th Ave. (P.O. Box 3141)
Portland, OR 97208
(503) 234-3361 [1-E, 4-E]

Baker, Glenn E.
Fire Management Officer
USDA-FS Willamette National Forest
211 E. 7th Ave.
Eugene, OR 97401
(503) 425-6533 [1-M, 3-M, 4-M]

Baker, Junius (Joe) O.
Fire Management Specialist
USDA-FS, Aviation and Fire Management
P.O. Box 2417
Washington, D.C. 20013
(703) 235-8666 [1-M, 1-R]

Bjorklund, Norm E.
Vice President
Industrial Forestry Association
1220 S.W. Columbia St.
Portland, OR 97201
(503) 222-9505 [1-M, 1-E, 3-E, 4-E]

Bray, David C.
Air Prog. Branch
USEPA
Region X, MS-625
1200 6th Ave.
Seattle, WA 98101
(206) 442-1125 [2-M, 2-R]

Brunn, Russell
Meteorologist
Oregon State Department of Forestry
2600 State St.
Salem, OR 97310
(503) 378-2506 [2-M, 4-R]

Campbell, R.A.
Ministry of Forestry
Province of British Columbia
Victoria, B.C.
(604) 387-5965 [1-M]

Chandler, Craig C.
Director
USDA-FS, Forest Fire and Atmospheric
Science Research
P.O. Box 2417
Washington, D.C. 20013
(703) 235-8195 [1-R, 2-R, 3-R, 4-R]

Clarke, Edward H.
Program Manager
Forest Residues Program
USDA-FS PNWF & RES
809 NE 6th Ave. (P.O. Box 3141)
Portland, OR 97208
(503) 234-3361 [1-E, 1-M]

Cleary, Brian D.
Extension Forester
Oregon State University
Forest Research Laboratory
Corvallis, OR 97331
(503) 753-9166 [1-M]

Core, John E.
Department of Environmental Quality
State of Oregon
P.O. Box 1760
Portland, OR 97207
(503) 229-6458 [2-M, 2-R]

Corlett, James B.
Manager, Oregon Forest Protection Association
1326 American Bank Bldg.
Portland, OR 97205
(503) 226-462 [1-M]

Cornelius, Royce O.
Director of Forest Resource Relations
Weyerhaeuser Company
Tacoma, WA 98401
(206) 924-2326 [1-M, 3-M, 4-M]

Craig, Charles D.
Air Resources Center
Oregon State University
Corvallis, OR 97331
(503) 754-4955 [2-R]

Currier, Raymond A.
Associate Professor
Forest Reseach Laboratory
Oregon State University
Corvallis, OR 97331
(503) 753-9166 [4-R]

Debell, Dean S.
USDA-FS PNWF & RES
Rt. 4, Box 500
Olympia, WA 98502
(206) 434-9470 [2-R]

Dell, John D.
Fuels Management Specialist
USDA-FS, PNW
319 Pine St.
Portland, OR 97208
(503) 221-2931 [1-M, 2-M, 3-M, 4-M]

Denison, James M.
Division-Forester
Publishers' Paper Times Mirror
P.O. Box 370
Toledo, OR 97391
(503) 336-2203 [1-M, 3-M, 1-E, 3-E]

Durham, Richard L.
Special Projects Officer
U.S. Department of Energy
P.O. Box 550
Richland, WA 99352
(509) 942-6553

Ellis, Thomas H.
Economist
FDA-FS, Forest Products Laboratory
P.O. Box 5130
Madison, WI 53705
(608) 257-2211 [4-E]

Feddern, Edward T.
Division Forester
Publishers Paper Times Mirror
P.O. Box 471
Tillamook, OR 97141
(503) 842-5551 [1-M, 3-M, 1-E, 3-E]

Fosberg, Michael A.
USDA-FS RMF & RES
240 W. Prospect St.
Ft. Collins, CO 80521
(303) 221-4390 [2-R]

Fox, Douglas G.
USDA-FS RMF & RES
240 W. Prospect St.
Ft. Collins, CO 80521
(303) 221-4390 [1-R, 2-R]

Freeburn, Scott
State of Oregon
Department of Environmental Quality
16 Oak Way Mall
Eugene, OR 97401
(503) 686-7601 [2-M, 2-R]

French, Richard E. (Dick)
Prevention and Protection
USDI - BIA
1425 NE Irving (P.O. Box 3785)
Portland, OR 97208
(503) 234-3361, Ext. 4740 [1-M, 3-M, 4-M]

Fritschen, Leo
School of Forestry
University of Washington
Seattle, WA 98195
(206) 543-6210 [1-R, 2-R]

Graf, Fred
District Forester
State of Oregon Department of Forestry
Star Route 2, Box 1-B
Philomath, OR 97370
(503) 929-3266 [1-M, 3-M, 4-M]

Hall, Frederick C.
Plant Ecologist
USDA-FS, PNW
319 SW Pine St.
Portland, OR 97208
(503) 221-3817 [1-M, 3-M]

Haddow, Dennis
Air Quality Bureau
Department of Environmental Health and Science
State of Montana
Helena, Montana 59601

Hartman, Harold E.
Environmental Specialist
Industrial Forestry Association
1220 SW Columbia St.
Portland, OR 97201
(503) 222-9505 [1-M, 3-M, 4-M]

Hedin, Albert T.
Forester
Washington State Department of Natural Resources
General Administration Building
Olympia, WA 98504
(206) 753-5350 [1-M, 2-M, 3-M]

Hickerson, Carl W.
Director, Fire Management
USDA-FS PNW
319 Pine St.
Portland, OR 97208
(503) 221-2931 [1-M, 3-M]

Hooven, Edward F.
Associate Professor, Wildlife Ecology
Forest Research Laboratory
Oregon State University
Corvallis, OR 97331

Hough, Walter A.
Staff Fire Scientist
USDA-FS, Forest Fire and Atmospheric
Science Research
P.O. Box 2417, Washington, D.C. 20013
Washington, D.C. 20013
(703) 235-8195 [1-R, 2-R]

James, Donald H.
Supervisor
USDA-FS Siuslaw National Forest
P.O. Box 1148
Corvallis, OR 97330
(503) 757-4493 [1-M, 3-M]

Johansen, Ragnar (Bill) W.
Principal Research Forester
USDA-FS, Southern Forest Fire Laboratory
Southeastern Forest Experiment Station
P.O. Box 5106
Macon, GA 31208
(912) 746-1477 [1-R, 2-R]

Keesee, Robert H.
Senior Economist
Georgia-Pacific Corporation
900 SW Pine St.
Portland, OR 97204
(503) 222-5561 [1-E, 3-E, 4-E]

Krauss, Paul E.
Deputy Supervisor
Washington State Department of Natural Resources
General Administration Building
Olympia, WA 98504
(206) 753-1935 [1-M, 3-M]

Kunz, Ralph H.
Fire Prevention and Fuel Management
USDA-FS PNW
319 Pine St.
Portland, OR 97208
(503) 221-2931 [1-M, 3-M]

Lamb, Robert C.
Formerly Regional Meteorologist
USDA-FS PNW
  Contact: Deeming, J.E.
  Regional Meteorologist
  USDA-FS PNW
  319 SW Pine Street
  Portland, OR 97208
  (503) 221-2931 [2-M, 2-R]

Lawrence, William
Research Coordinator
Weyerhaeuser Corporation
Centralia, WA
(206) 736-8241 [1-R, 4-R]

Lingler, Gene E.
District Silviculturalist
USDA-FS Siuslaw National Forest
Alsea, OR
(503) 487-5811 [1-M, 3-M]

Martin, Robert E.
Project Leader
USDA-FS PNW Bend Silviculture Lab
1027 NW Trenton Ave.
Bend, OR 97701
(503) 422-6283 [1-M, 1-R]

Matthews, Robert P.
Director - Forest Management
Washington Forest Protection Association
1411 4th Ave. Bldg.
Suite 1220
Seattle, WA 98101
(206) 623-1500 [1-M, 3-M, 4-M]

Maxwell, Wayne G.
Forest Residues Research
USDA-FS PNWF & RES
809 NE 6th Ave. (P.O. Box 3141)
Portland, OR 97208
(503) 234-3361 [1-R, 2-R, 3-R]

McCleese, William L.
Supervisor
USDA-FS, Ochoco National Forest
Prineville, OR 97754
(503) 447-6247 [1-M, 3-M, 4-M]

McLaughlin, William D.
Supervisor
USDA-FS Okanogan National Forest
219 2nd Ave., S.
Okanogan, WA 98840
(509) 422-2704 [1-M]

McMahon, Charles K.
Principal Research Chemist
USDA-FS, Southern Forest Fire Laboratory
Southeastern Forest Experiment Station
P.O. Box 5106
Macon, GA 31208
(912) 746-9436

Mick, Allen H.
Senior Environmental Engineer
Georgia-Pacific Corporation
900 SW 5th Ave.
Portland, OR 97204
(503) 222-5561 [1-M, 2-R]

Monteith, Lee E.
Senior Chemist
Department of Environmental Health
University of Washington
Seattle, WA 98195
(206) 543-4252 [2-R, 4-R]

Mote, David
Manager Land and Timer Resources Group
International Paper Company
121 SW Salmon
Portland, OR 97204
(503) 243-3259 [1-M, 3-M, 4-M]

Murphy, James L.
Wildfire Prevention
USDA-FS PSWF & RES
1960 Addison
Berkeley, CA 94701
(415) 449-3482 [1-M, 2-R]

Mutch, Robert
Fire Management Specialist
USDA-FS Lolo National Forest
Missoula, MT 59801
(406) 585-3011 [1-M, 1-R]

Newton, Michael
Associate Professor
School of Forestry
Oregon State University
Corvallis, OR 97331
(503) 753-9166 [1-M, 4-R]

Paulson, Neil R.
Air Quality Management Officer
USDA-FS, Aviation and Fire Management
P.O. Box 2417
Washington, D.C. 20013
(703) 235-8666 [2-M, 2-R]

Pickford, Stewart G.
Assistant Professor
College of Forest Resources AR-10
University of Washington
Seattle, WA 98195
(206) 543-6210 [1-R, 2-R]

Pierovich, John M.
Program Manager
USDA-FS, Southern Forest Fire Laboratory
Southeastern Forest Experiment Station
P.O. Box 5106
Macon, GA 31208
(912) 746-1477 [2-R, 3-R]

Rey, Mark E.
Environmental Forester
National Forest Products Association
1619 Massachusetts Ave., NW
Washington, D.C. 20036
(202) 797-5869 [1-M, 3-M, 1-E, 3-E]

Roberts, Charles F.
Principal Research Meteorologist
USDA-FS, Aviation and Fire Management
P.O. Box 2417
Washington, D.C. 20013
(703) 235-8666 [2-R]

Robertson, John R.
Data Management Leader
USDA-FS PNW
319 SW Pine St.
Portland, OR 97208 [1-M]

Rosene, John
Olympic Air Pollution Control Authority
120 East State Ave.
Olympia, WA 98501
(206) 352-4881 [2-M, 2-R]

Ryan, Paul W.
Principal Research Forester
USDA-FS, Southern Forest Fire Laboratory
Southeastern Forest Experiment Station
P.O. Box 5106
Macon, GA 31208
(912) 746-9436 [1-R, 2-R]

Sandberg, David V.
Forest Residues Program
USDA-FS PNWF & RES
4507 University Way, NE
Seattle, WA 98105
(206) 442-7815 [1-R, 2-R]

Shenk, William D.
Cooperative Fire Management
USDA-FS, PNW
319 SW Pine St.
Portland, OR 97208
(503) 221-2727 [1-M]

Shrader, Paul H.
Deputy Director
Northwest Energy Policy Project
1096 Lloyd Bldg.
700 N.E. Multnomah St.
Portland, OR 97232
(503) 234-9666 [4-R]

Stenkamp, Paul R.
USDA-FS, Gifford Pinchot National Forest
500 W. 12th St.
Vancouver, WA 98660
(206) 696-4041 [1-M, 3-M, 1-E, 3-E]

Strand, Robert
Research Forester
Central Division Research
Crown Zellerbach Corporation
Wilsonville, OR
(503) 682-2141 [1-R, 4-R]

Teitel, Jeff
Environmental Counsel on Air Quality
National Forest Products Association
1619 Massachusetts Ave., NW
Washington, D.C. 20036
(202) 797-5868 [2-M, 2-R]

Todd, John E.
Director of Timber Management
USDA-FS PNW
319 SW Pine St.
Portland, OR 97208
(503) 221-2955 [1-M]

Tokarczyk, Robert D.
Forest Supervisor
USDA-FS, Gifford Pinchot National Forest
500 W. 12th St.
Vancouver, WA 98660
(206) 696-4041 [1-M, 3-M, 1-E, 3-E]

Torrence, James F.
Deputy Regional Forester
USDA-FS PNW
319 SW Pine St.
Portland, OR 97208
(503) 221-3627 [1-M]

Truax, Michael R.
Resource Planning Analyst
Simpson Timber Company
900 Fourth Ave.
Seattle, WA 98164
(206) 292-5217 [1-M, 3-M, 4-M]

VanSickle, Charles C.
Forest Survey
USDA-FS, PNW F & RES
809 NE 6th Ave
Portland, OR 97208
(503) 429-3361, Ext. 4935 [1-M, 1-E]

Ward, Darold E.
School of Forestry
University of Washington
Seattle, WA 98195
(206) 543-6210 [1-R,2-R]

Ward, Frank R.
Forest Residues Research
USDA-FS PNWF & RES
809 NE 6th Ave. (P.O. Box 3141)
Portland, OR 97208
(503) 234-3361 [1-R, 2-R, 3-R]

Weaver, Darrell F.
Meteorologist, Air Programs
State of Washington Department of Ecology
Olympia, WA 98504
(206) 753-2800 [2-M, 2-R]

Wells, Stuart N. Jr.
Operations Director
Forest Protection Division
State of Oregon Department of Forestry
2600 State Street
Salem, OR 97310
(503) 378-2506 [1-M, 2-M]

Williams, Dansy (Dan) T.
Principal Research Meteorologist
USDA-FS, Southern Forest Fire Laboratory
Southeastern Forest Experiment Station
P.O. Box 5106
Macon, GA 31208
(912) 746-5191 [1-R, 2-R]

Zerbe, John I.
Program Manager
USDA-FS Forest Products Laboratory
P.O. Box 5130
Madison, WI 53705
(608) 257-2211 [4-R]